RESEARCH REPORT

EARTHQUAKE RESISTANT MODULAR HOME FOUNDATION SYSTEM

EXTERNAL
RESEARCH
PROGRAM

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REPORT

"EARTHQUAKE RESISTANT MODULAR HOME FOUNDATION SYSTEM"

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PURPOSE

In recent years, Canadian manufacturers and exporters have captured a significant share of the Japanese import housing market, and while that market has been battered by the recent slumps in the Asian economies, it still represents an important component of Canada's overall export strategy. However, increasing competition from other exporting nations and the continued evolution and improvement in Japan's residential construction industry could put these exports at risk.

One response to such pressures is to lower prices; however, this can be a counterproductive strategy as it lowers profits for Canadian suppliers, raises concerns in the consumers' minds about product quality "You get what you pay for." and it places these export homes in the realm of commodities wherein price is the sole determining factor. This last aspect leaves Canadian products particularly vulnerable to competition from manufacturing industries in many low-cost developing nations. An alternate and potentially more beneficial approach is to offer greater product differentiation vis-a-vis our competitors by introducing improved products which respond more directly to Japanese technical and lifestyle or market driven concerns. This report explores such an approach.

This report suggest development of a "Canadian Home Concept" which integrates Canada's leading materials and construction technologies with key 'value-added' components to create a unified product offering under the umbrella of a Canadian home whose whole is greater than the sum of its parts. The report focuses on that 'value-added' component and to this end discusses the development, evaluation and introduction of improved seismic or earthquake resistance for Canadian homes exported to Japan. While the work builds on an earlier CMHC related project titled " RORO MODULAR HOME SHIPPING SYSTEM", it has equal application for pre-cut, 2x4 and panelized export housing products.

The work also recognizes the continuing efforts by various Canadian agencies to support and promote the wider use of multi-storey and multi-family wood framed structures in Japan and to that end, the work investigated the role of the proposed seismic restraint system as it might apply to those types of structures. The report also contains a preliminary comparative costing analysis of the seismic resistive foundation systems versus the more conventional concrete crawl-space foundations which are typical to both single family and multi-family structures and while these improved systems are more expensive in the single family environment, it appears that when used in support of multi-family structures that seismic resistant foundations may offer a combination of improved earthquake protection *and* reduced construction costs.

The report concludes with an overview of the subsequent project work which would have to be undertaken to develop, conclusively test and properly disseminate information about these systems to the Canadian manufacturing and export industries and to the Japanese residential builders and home buyers.

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Third Secretary, Commercial, Canadian Embassy , TOKYO

Mr. Zimmerman provided valuable information regarding the Japanese housing market and helped to forge contacts with individuals and organizations active in the residential insurance market.

Mr. Shosaku Okano
Atarashi Co. Ltd. , Builder, OSAKA

Mr. Okano and the Atarashi staff were instrumental in developing base pricing information on the production of conventional crawl space foundations for 2x4 homes in Japan.

Kuriyama Corporation , Builder, OSAKA

The Kuriyama staff provided both construction details and costing information as it relates to conventional crawl space foundations for 2x4 homes in Japan.

Mr. Shunichi Hokura
Executive Director, Registered Organization for Warranted Houses, TOKYO

Through his housing organization, Mr. Hokura provided information on earthquake insurance rates for 2x4 wood framed homes in Japan.

EXECUTIVE SUMMARY

Chapter 1: INTRODUCTION

This Chapter provides an overview of the project background and objective. It further briefly describes the nature and impact of a typical earthquake and discusses the cause of quake damage. It concludes with a explanation of the difference between 'structural protection' and 'continued functionality' in a residence.

Chapter 2: ORIGINAL CONCEPT DEVELOPMENT

Discusses the genesis of the 'floating slab' concept which was originally proposed and alternate 'ad-hoc' or site produced quake protection systems and explains why they could not meet the project objectives. It concludes by discussing the role of the RORO Modular Home as the project vehicle for design and evaluation.

Chapter 3: PERFORMANCE OF WOOD FRAMED HOMES

This section deals with a technical presentation of alternate conventional seismic resistant or damage mitigating construction approaches, and further describes the past performance of wood framed homes, anticipated design loads and expected performance utilizing the quake mitigation strategies being considered.

Chapter 4: PASSIVE PROTECTIVE SYSTEMS

Looks at a variety of damping and resistive earthquake protection technologies; describing the advantages and disadvantages of each. It also establishes formalized selection criteria and applies a selection process to the technologies which are reviewed.

Chapter 5: PROPOSED PROTECTION : SLIDER-SPRING SYSTEM

This highly illustrated Chapter describes in detail the construction, installation and use of the seismic sliders and springs upon which the earthquake mitigation strategy is based. Further, it explains the need to introduce 200 mm thick pre-cast concrete slabs between the modules, used in this project, and the seismic foundations.

Chapter 6: ANALYTICAL VERIFICATION

The work describes the computer simulations runs which incorporated the seismic resistant foundation in a modular home assembly and compared its performance to a more traditional foundation system. The results indicated how the protected modular home might have performed had it been subjected to the ground shaking during the 1994, Northridge; 1995, Kobe; and the 1977 San Fernando quakes. It also discusses the impact of wind on the system and provides conclusions about the overall suitability of the seismic protection system.

Chapter 7: ARCHITECTURAL CONSIDERATIONS

The discussion touches on the many other issues which must be considered when contemplating a seismic protection approach. These include the service connections, attachment of porches, steps and overhangs such as carports. Finally the section looked at a potential closure system to surround or enclose the base of the home.

Chapter 8: APARTMENT APPLICATION.

While the work focusses on the seismic protection of a home, this Chapter looked at the application of the seismic resistant foundation approach to a modular , three-storey, wood-framed apartment building and provides an overview of its potential impact.

Chapter 9: COMPARATIVE COST ANALYSIS.....

The costing analysis shows that while the earthquake resistant foundation is slightly more than twice the cost of a conventional home foundation, it is comparatively less-expensive and more effective than comparable levels of insurance and only adds 3% -3.5% to the cost of a typical Japanese home but provides a considerable increase in consumer benefit. Most interestingly, the work also suggest that for wood-framed apartment buildings, an earthquake resistant foundation system is actually less expensive than traditional non-protective foundations.

Chapter 10: SUMMARY CONCLUSIONS.....

This Chapter provides a point form summary of the conclusions noted throughout the report.

Chapter 11: PROPOSED FUTURE RESEARCH.....

Despite the breadth of the work undertaken and discussed in this report, further efforts need to be made to conclusively demonstrate the effectiveness of the seismic resistant foundation system in a modular home setting to an engineering certainty. This Chapter outlines the work required to meet that standard and suggest a potential timetable, work programme and budget for meeting that challenge.

RÉSUMÉ

Chapitre 1 : INTRODUCTION

Ce chapitre donne un aperçu du contexte et de l'objectif de la recherche. De plus, il décrit brièvement la nature et l'incidence d'un séisme type et traite de la cause des dommages en résultant. En guise de conclusion, il explique la différence entre «la protection de la charpente» et «la poursuite de la fonctionnalité» d'une habitation.

Chapitre 2 : CONCEPT ORIGINAL

Le chapitre remonte à l'origine du concept de «dalle flottante» alors proposé ainsi que des systèmes de protection réalisés sur place ou d'autres systèmes spéciaux, en plus d'expliquer pourquoi ils ne peuvent pas répondre aux objectifs de la recherche. Il conclut par un exposé portant sur le rôle de la maison modulaire RORO comme moyen de conception et d'évaluation.

Chapitre 3 : PERFORMANCE DES MAISONS À OSSATURE DE BOIS

Le chapitre livre un exposé technique des autres méthodes de construction classiques visant à rendre le bâtiment résistant aux séismes ou à en réduire les dommages, et décrit davantage la performance passée des maisons à ossature de bois, les charges de calcul anticipées et la performance attendue en exploitant les mesures d'atténuation des effets des séismes envisagées.

Chapitre 4 : SYSTÈMES DE PROTECTION PASSIFS

Le chapitre envisage différentes technologies d'amortissement ou de résistance aux séismes, èn plus de décrire les avantages et les désavantages de chacune. Il établit également des critères de sélection adoptés officiellement et applique un mode de sélection pour les technologies passées en revue.

Chapitre 5 : PROTECTION PROPOSÉE - SYSTÈME À COULISSES ET À RESSORTS

Le chapitre abondamment illustré décrit en détail la construction, l'installation et l'utilisation de coulisses et ressorts antisismiques sur lesquels se fonde la stratégie d'atténuation des effets des tremblements de terre. De plus, il explique la nécessité de mettre en place des dalles en béton préfabriqué de 200 mm d'épaisseur entre les modules, ce qui a été utilisé pour les besoins de la présente recherche, et des fondations antisismiques.

Chapitre 6 : VÉRIFICATION ANALYTIQUE

Le travail décrit les simulations informatiques portant sur les fondations antisismiques d'une maison modulaire en comparant leur performance par rapport à des fondations classiques. Les résultats indiquent comment la maison modulaire protégée aurait pu se comporter si elle avait eu à subir les séismes de Northridge en 1994, de Kobe en 1995 et de San Fernando en 1977. Il traite

aussi de l'incidence du vent sur le système et livre des conclusions quant à l'à-propos général du système de protection contre les séismes.

TABLE of CONTENTS

Chapter 1: INTRODUCTION 1

1.1 Introduction
1.2 Project Goal
1.3 Chosen Approach - Earthquake Resistance 2
1.4 Brief Background on Earthquakes
1.5 Protection " Structural -vs- Functional 3

Chapter 2: ORIGINAL CONCEPT DEVELOPMENT 4

2.1 Original Concept
2.2 RORO Home Selection
2.3 Preliminary Approach & Findings
Separated Slab-on-Grade .....
Slab-on-Grade 7
Site Built Sliders
Conclusions

Chapter 3: PERFORMANCE OF WOOD FRAMED HOMES 8

3.1 Building Response to Earthquakes
Rigid High Strength Structures
Rigid Limited Strength Structures
Flexible Strong Structures
Flexible Limited-Strength Structures 9
3.2 Wood Framed House Response to Earthquakes
3.3 Past Performance .....
3.4 Earthquake Loads in Japan 10
3.5 Expected Performance 11

Chapter 4: PASSIVE PROTECTIVE SYSTEMS 12

4.1 Seismic Isolation Systems
Rubber Bearings
Lead-Rubber Bearings
Flat Friction Sliders 13
Friction Pendulum Sliders
Other Isolation Systems 14
4.2 Energy Dissipation Systems
Viscous Dampers
Friction Dampers
Hysteretic Dampers

4.3 Selection Criteria..... 15
4.4 Selection of a Protective System
Dampers
Isolation
Rubber and Lead-Rubber Bearings..... 16
Sliders
Friction Pendulum Sliders
Combination System with Flat Sliders and Rubber Springs..... 17

Chapter 5: PROPOSED PROTECTION : SLIDER-SPRING SYSTEM..... 18

5.1 General description
5.2 Foundations
5.3 Sliders
5.4 Stainless Steel Plates
5.5 Linear Shear Springs..... 20
5.6 Concrete Slabs
5.7 Modules

Chapter 6: ANALYTICAL VERIFICATION..... 25

6.1 Seismic Weight
6.2 Analytical Model
Diagonal Braces
Sliders..... 27
Linear Shear Springs
6.3 Earthquake Loading
6.4 Results..... 28
6.5 Analysis Summary..... 32
Storey Drift
Floor Accelerations
Base Shear
Isolation Plane Displacement
6.6 Wind Load Analysis..... 33
6.7 Conclusions

Chapter 7: ARCHITECTURAL CONSIDERATIONS..... 35

7.1 Introduction
7.2 Services
Sewer Lines..... 36
Power & Communications 37
Water-Gas & Kerosene Lines or Pipes

7.3 Attached Structures
Porches & Steps 38
Minor Porch & Entry Roofs
Carport and Major Porch Roofs

7.4 Landscaping & Grade Finish 39
Landscaping
System Closure 40
7.5 Post Quake Remediation 41
7.6 Alternative Structural Systems

Chapter 8: APARTMENT APPLICATION 42

8.1 Introduction
8.2 System Design
8.3 Analysis
Assumptions
Application
8.4 Summary 44

Chapter 9: COMPARATIVE COST ANALYSIS 46

9.1 Introduction
9.2 Costs 47
9.3 Cost Analysis & Impacts
Mortgage Costs
Insurance Costs 49
9.4 Apartment Costs

Chapter 10: SUMMARY CONCLUSIONS 51

Chapter 11: PROPOSED FUTURE RESEARCH 52

11.1 Proposed Activities
11.2 Duration 53
11.3 Budget

REFERENCES or BIBLIOGRAPHY 54

LIST of FIGURES

Figure 1:	Seismic Attributes: Hyogo-Ken Nambu Earthquake (Kobe) Jan.17,1995	2
Figure 2:	Typical Modular RORO Home Plan - Main Floor	5
Figure 3:	Typical Modular RORO Home - Representative Elevation	6
Figure 4:	Example of a Dynamic Load Deformation Curve of a OSB Panel [10]	10
Figure 5:	[a] Non-isolated Building Response [b] Isolated building Response (DIS Inc.)	12
Figure 6	[a] Rubber Bearing (Enidine) [b] Lead-Rubber Bearing (Enidine)	13
Figure 7:	[a] Flat Slider (DIS Inc.) [b] Friction Pendulum Slider (FHWA)	13
Figure 8:	[a] Viscous Damper (Taylor) [b] Hysteretic Damper (FHWA)	14
Figure 9	Proposed Earthquake Resistant Slider and Spring Details	19
Figure 10:	Seismic Resistant Foundation Configuration - Plan	21
Figure 11	House Section "A" Showing Earthquake Resistant Foundation System	22
Figure 12	House Section "B" Showing Earthquake Resistant Foundation System	24
Figure 13:	SAP2000 Wire Frame Model of 2 Storey Home Used in Verification Study	26
Figure 14:	Panel Forces and Deformation	27
Figure 15:	Force Deformation Plots First Floor Panels During Northridge Record Analysis	32
Figure 16:	Construction Section at Access Hatch and Service Sleeve	35
Figure 17::	Typical Post and Stair Bearing Detail	38
Figure 18:	Carport Foundation / Roof Plan	39
Figure 19:	Carport Section	39
Figure 20:	Home Closure Detail at Grade	40
Figure 21	Analysis of Wind Loads on Prototypical Apartment Structure - Representative Section	43

LIST of TABLES

Table 1:	Dampers: Selection Criteria Rating	15
Table 2:	Lead-Rubber Bearings : Selection Criteria Rating	16
Table 3:	Slider Spring System: Selection Criteria Rating	17
Table 4:	Coefficient of Friction Values	18
Table 5:	Properties of Brace Elements	26
Table 6	Properties of Slider Elements	27
Table 7:	Properties of Spring Elements	27
Table 8:	Earthquake Records Used in Analysis	28
Table 9	Northridge Record Amplified Input Parameters Used for Simulation	29
Table 10:	Northridge Record Output Parameters from Analysis	29
Table 11:	Kobe Record Amplified Input Parameters Used for Simulation	30
Table 12	Kobe Record Output Parameters from Analysis	30
Table 13:	San Fernando Record Amplified Input Parameters Used for Simulation	31
Table 14:	San Fernando Record Output Parameters from Analysis	31
Table 15:	Wind Load Forces	33
Table 16:	Wind Load Return Period Conversion	33
Table 17:	Wind Load System Displacement	33
Table 18:	Comparative Japanese Foundation Costs - Traditional vs Earthquake Resistant	48

CHAPTER ONE : INTRODUCTION

1.1: Introduction

The export of building products and various forms of housing components and assemblies has been a notable success for Canadian manufacturers in recent years; particularly, exports to Japan and other Asian markets. However, that area's economic slump in the late 90's, known as the 'Asian Flu' has dramatically slowed those exports. Concurrently, other exporting nations have become more competitive thus further limiting the scale and success of traditional marketing efforts. Finally, there is some concern that the panelized housing market which has been at the core of the export housing boom is vulnerable to displacement by local Japanese firms. Those companies can master the relatively low technology of the underpinning panels and consequently achieve significant savings by eliminating any premiums paid to Canadian manufacturers and the trans-Pacific shipping costs.

Against this background, the Canadian housing industry must continue to raise standards, lower costs and *develop new products or services* in order to remain competitive and retain their market share, or they risk being replaced by those countries and industries who do.

1.2: Project Goal

The goal of this project was to devise a technical breakthrough or marketing strategy which would increase the sales of Canadian export homes. While the work focussed on modular homes, it was hoped that any resulting solution would also have application in the broader Canadian 2x4 and panelized housing export markets. Further, the work focussed on the Japanese market although the eventual solution which was developed is not limited to any geographic or market area, but rather has application in any locale with similar earthquake conditions.

Modular housing was chosen as the primary export product for investigation for two primary reasons:

First:

Modular construction contains a higher percentage of Canadian labour and materials content than the conventional 2x4 or panelized export products which currently form the bulk of Canada's housing exports. Preliminary calculations suggest that modular homes contain approximately 400% more Canadian content, 56%-vs-15%, than more traditional panelized export homes. Consequently, even a modest increase in the market share of these higher " value added" products has a more significant impact on the value of our exports and subsequent beneficial impact on Canadian industry.

Secondly:

Recent years have seen a considerable effort by various players such as the Japanese construction industry, the Japanese and US governments, and Canada, through CMHC and the Canadian Wood Council to first secure approval for, then use of, wood framing in low-rise, three and four storey multi-family, structures. They have also extensively promoted this product within the Japanese marketplace. This type of large-scale repetitive building form is ideally suited to modular construction. Consequently, any Canadian induced technical advances in this area might significantly increase Canada's image and thus its marketing edge.

1.3: Chosen Approach - Earthquake Resistance

The technical approach which was chosen to provide the export marketing edge was *increased earthquake resistance*. Because there are great similarities between Canadian, American and Scandinavian wood-frame systems, it was felt that something was required to provide highly identifiable product differentiation. Also, framing advances and environmental approaches such as the 'Healthy Home' can be adapted with fair ease by either the importing nation or our exporting competitors. Consequently, it was felt that development of a new patent able "Earthquake Resistant Foundation" [ERF] system for use exclusively as part of a broader "Canadian Home Concept" offering, might afford Canadian exporters a marketing edge. While this work did not lead to a patent able solution, use of the technical approach developed in this project will allow Canadian housing exporters the opportunity to offer a superior, more comprehensive, and in multi-family projects, less expensive housing.

1.4: Brief Background - Earthquakes

To assist in understanding the following discussions, it helps to have a brief appreciation of the nature and impact of earthquakes. Contrary to general perceptions, quakes are neither long duration nor do they generally involve massive building displacements. Rather, they might more generally be thought of as a series of short, sharp 'jerks' of the ground and the various structures supported either on, or in that ground.

For example, the following Figure # 1, graphically illustrates one example of the ground shaking recorded during the 1995 Kobe, Japan quake which is more properly known as the "Hyogo-Ken Nambu Earthquake".

These results from just one recording station indicate that the quake lasted essentially 15 seconds, the maximum ground acceleration was about 0.8g or 80% of gravity and the maximum displacement was only 27.1 cm.

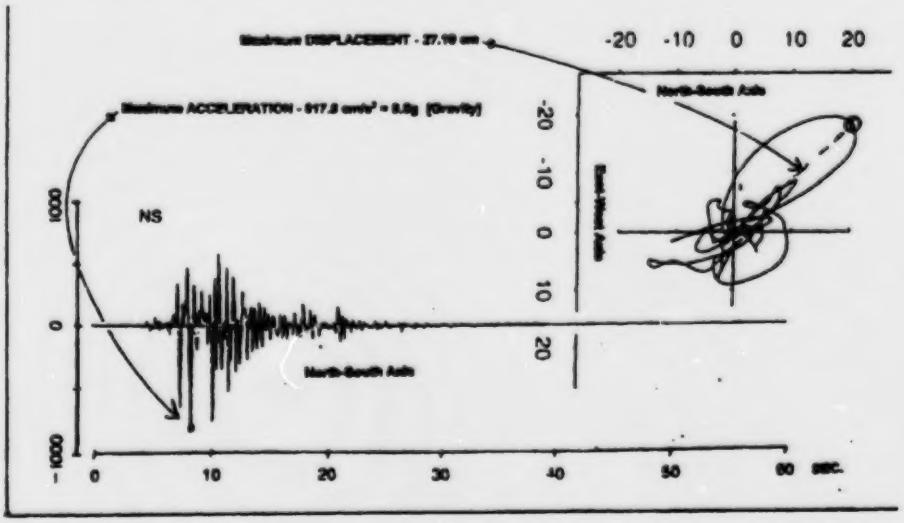


Figure # 1 Seismic Attributes - Hyogo-Ken Nambu Earthquake (Kobe) January 17.1995

Despite this'limited' action, the quake killed more than 5,500 people; injured 41,500; destroyed 100,000 buildings and severely damaged 107,000 more.

1.5: Protection: "Structural -vs- Functional"

It would not be inappropriate to suggest that the primary focus of most engineered seismic protection is oriented towards life safety. That is to say: 'ensuring that buildings don't fall down and kill people during very severe earthquakes'. In this approach it generally doesn't matter to what degree windows break, drywall cracks, services are broken or how much non-life- threatening damage is sustained by broken furniture, overturned cabinets or non-functioning kitchens.

Conversely, the focus of **this** project is the 'initial safety **and continued functionality'** of the residence in a post-quake environment. This means no or minimal damage to finishes, retention of all services at the home and the general continued livability of that home following a moderate to severe quake.

The following chapters describe the evolution of this project, the proposed solution, resulting laboratory simulations and costing analysis. The work concludes by looking at how a ERF system developed for use with modular homes might be utilized in alternative situations such as a wood-framed, 3 storey apartment structure to provide an alternate, superior Canadian housing product for export to earthquake prone areas.

CHAPTER TWO: ORIGINAL CONCEPT DEVELOPMENT

2.1: Original Concept

This project grew out of three observations:

i) Modular homes generate very rigid structures due to the double wall construction between the units and the somewhat regimented rectangular form which is a natural attribute of the mass-production process from which they spring.

ii) Most 'westernized' Japanese homes tend to be built upon a relatively shallow crawl space foundation and although these spaces are not widely utilized, they are nonetheless of high quality, and thus expensive, and tend to incorporate a finished floor slab ranging from 100 mm -150 mm [4"-6"] in thickness.

iii) New and proven technologies such as Insulated Shallow Footings or Foundations [ISF] allow for slab-on-grade construction in even the coldest climates.

Integrating these observations led to the question:

> "Would it be possible to devise a low-cost slab foundation system upon which a modular home could 'float' during an earthquake as a means to minimize quake damages?"

This quest became the core of the project and against this background it explored the potential of creating a sliding plane foundation system to accommodate a prototypical modular home of the type manufactured in Canada and suitable for subsequent erection or assembly in Japan.

2.2 RORO Home Selection

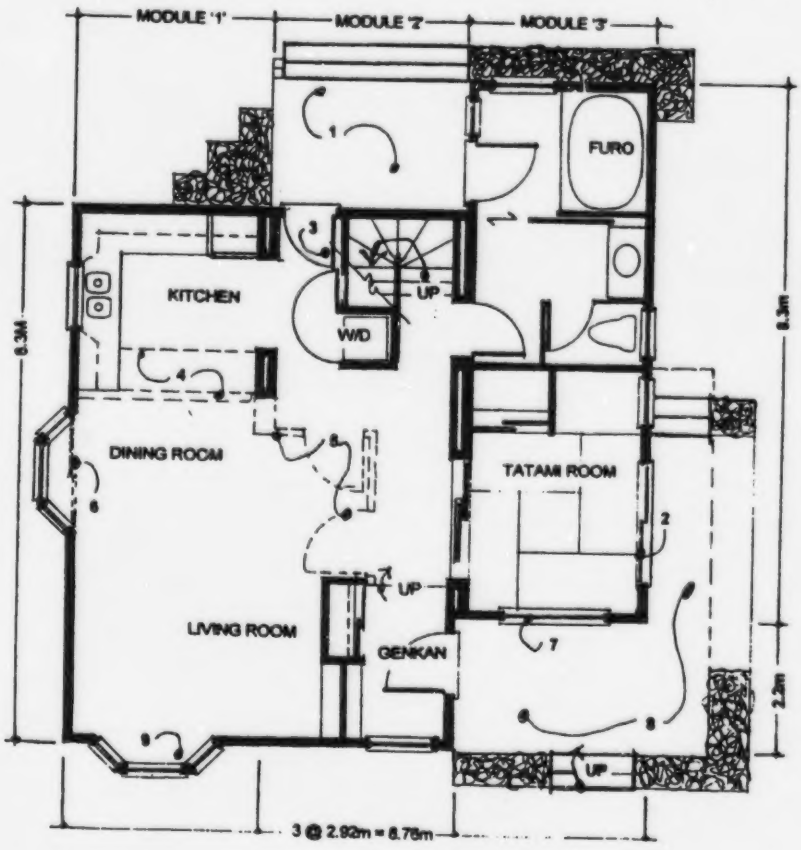
The project chose as its test vehicle a modular house design called the RORO House which had been developed in an earlier CMHC supported project to explore how modular homes might be produced in Canada and cost- effectively transported to Japan aboard the Roll-On / Roll-Off [RORO] car carriers which following delivery of their Japanese cars to North America return essentially empty to their Japanese home ports.

That project had suggested that a modular home could be delivered competitively versus more traditional panelized export products, and yet have a far higher quality and percentage of Canadian content. Those wishing further information on that study should contact the Canadian Housing Information Centre in Ottawa which can be reached by calling 1-800-668-2642 or through the CMHC web site: **www.cmhc-schl.gc.ca**

The RORO home plan and elevation are illustrated in Figures 2 & 3 on the following two pages. The house plan is not only reflective of the type of homes currently available to Japanese consumers, but it also allowed the exploration of the impact of any proposed earthquake resistant solution on a plan which was not a strict rectangle. Further, it allowed for the consideration of architectural features such as decks, carports and roof overhangs; issues which are discussed further in Chapter # 7:

2.3: Preliminary Approach & Findings

The original hope was to take advantage of slab foundation which is essentially present in all new Japanese homes and have it act as a sliding plane for the modular home. It was thought that by over sizing the slab in the areas of the modular bearing points by some 500 mm -600 mm in all directions from those bearing points that during a quake the ground and slab would move under the home thus minimizing any quake damage to the modular home itself.



OPTIONS:

1 Field supplied and installed rear deck and roof over.

2 Patio doors

3 Door c/w large glass panel

4 Eating counter

5 Dividing walls and doors.

6 Patio door or window

7 Optional window location

8 Entry deck, roof and planters field supplied and installed

9 Field installed, surface mounted bay window.

Figure 2 : Typical Modular RORO House Plan - Main Floor

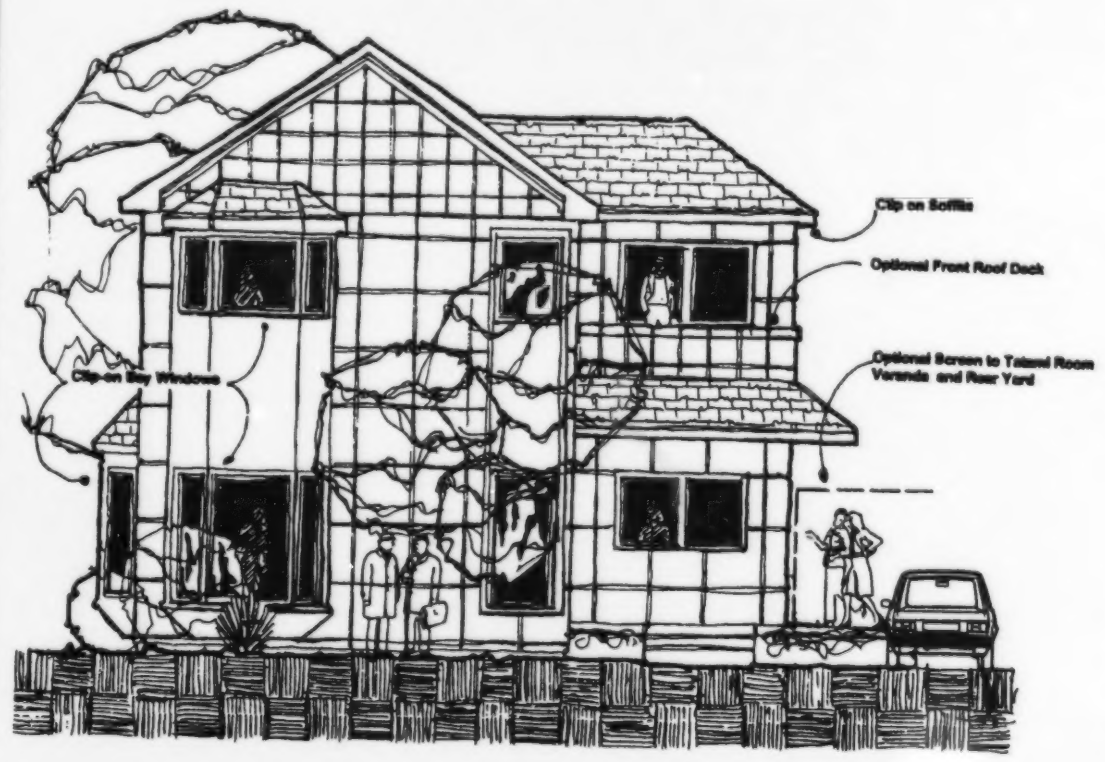


Figure 3: Typical Modular RORO House - Representative Elevation

However, upon consideration this was found to be impractical for a number of reasons:

i) One could not guarantee that over time that the module would continue to slide due to possible 'bonding' between the sliding surfaces or the possible build-up of grit and dirt between them.

ii) It was found that the modules had to resist greater lateral wind loads than seismic loads. Consequently, if the home was designed to move during a quake, it would also be subjected to undesirable lateral displacement during any severe winds. Conversely, if the home were sufficiently resistant to movement under wind forces, it would not behave in a way to mitigate the less severe seismic design loads.

iii) Finally, upon review, it was felt that a direct module to slab setting did not allow for proper inspections and maintenance of any major components or home services which may be required.

Given these initial findings, it became necessary to explore alternate construction configurations. Some of those other options are discussed below:

Separated Slab-on Grade

This concept explored a normal slab-on-grade which was to be fully separated from the ground by a layer of fine gravel or sand upon which it would remain somewhat stationary during a quake. In frost areas, the underlying ground was to be protected by an intermediate layer of ground insulation which was intended to mitigate or eliminate ground swelling due to frost heave.

Slab-on-Slab

In this configuration two concrete slabs would be separated by various elements such as sand, pea gravel or even bentonite panels. It was expected that the home modules would be securely attached to the upper slab with the expectation that during a quake, the home and upper slab would shift on the inter-slab layer to provide a degree of floating thus reducing the quake induced movement and damage.

Site-Built Sliders

This approach considered a variety of site assembled sliders such as oil-separated steel plates, teflon-steel combinations plus steel plates on ball bearings or rollers.

Conclusions

Each of the proposal in the above groups was eventually rejected either because of a lack of reliable information on how the various interfaces might react; such as using sand as a slider plane, or concerns about the long-term viability of the systems which have not been tested in a long-term open air environment.

Researchers were equally unsure if steel bearings could remain untested for a number of years and then suddenly react as expected , or more importantly, as needed. Might there be a bonding of the steel surfaces or would rust or grit interfere with the required smooth lateral displacements?

These concerns led to the eventual elimination of all of the what might be described as ad-hoc or low-tech options. It became evident that in order to achieve the instantaneous performance and long-term reliability set as project objectives, that it would be necessary to consider other proven seismic protection options. The remainder of this report discusses the review, evaluation and analysis of these more advanced and proven seismic protection systems , but does so within the context of the single family residence.

CHAPTER THREE: PERFORMANCE of WOOD FRAMED HOMES

3.1 Building Response to Earthquake

Lateral loads during seismic shaking arise from the mass of the building being moved by the ground. In a building, the mass is mostly concentrated at floor and roof levels. As the ground accelerates and decelerates, the mass follows provided that there is a strong enough link to overcome the inertia forces acting on the masses. Inertia can be thought of as the tendency of a mass to maintain a steady motion with a constant velocity. As the ground and the building move, the building may amplify or de-amplify the motion of the ground depending on the dynamic properties of the building. If the natural frequency of the building is close to the dominant frequency of the earthquake excitation, the motion is amplified, and if the match is close to perfect, a condition called 'resonance' occurs. The degree of amplification depends on the ability of the building to dissipate energy through damping.

There are various sources of damping in a wood building, such as a home, the most prominent being the friction between components of the building, both structural and non-structural. With increasing response, damping tends to increase. If the response is large enough to cause damage by bending and pulling of nails and by cracking of shear panels, the damping level increases dramatically.

Two parameters are commonly used to describe the level of response of a building: the maximum acceleration of a floor or 'floor acceleration' and the maximum relative displacement between floors or 'storey drift'. In terms of the performance of a building during an earthquake, a high floor acceleration may cause damage to the contents of the building. Storey drift may indicate the level of structural damage sustained by the lateral load resisting system. Building types based on their response to earthquake are described briefly below.

RIGID HIGH-STRENGTH STRUCTURES

If these buildings are founded on stiff soil they will probably resonate with the earthquake and respond with large accelerations but small storey drifts. Because this type of building is sufficiently strong it may not suffer structural damage. However, the contents may be damaged due to high floor accelerations. A good example is the performance of the Los Angeles Medical Centre, which being a very strong rigid structure did not suffer any significant structural damage during the 1994 Northridge earthquake, but was rendered non-functional due to severe damage to the equipment inside.

RIGID LIMITED-STRENGTH STRUCTURES

When these buildings are supported by rigid soil they will initially resonate with the earthquake, with accelerations increasing until the inertia forces exceed the capacity of the lateral force-resisting system, such as shear walls. The damage to the building may be indicated by large storey drifts. Collapse will not occur if the system is 'ductile', which means that it is detailed to undergo large deformations without losing its gravity load-carrying capacity. The contents of the building will suffer to a lesser degree, but this may be irrelevant as the building is damaged and probably unfit for immediate use.

Most buildings designed to current codes are expected to perform as 'Rigid Limited-Strength Ductile' systems with sufficient ductility to undergo substantial storey drifts without collapse. This approach is adopted because it is generally too expensive to provide adequate strength to prevent structural damage from a possible earthquake which may never occur. Further, if the added strength has the effect of increasing the floor acceleration and thus leading to increased damage to contents, the increased structural costs outweigh any overall benefits.

FLEXIBLE STRONG STRUCTURES

Buildings of this type perform in the most satisfactory manner when supported by rigid soil. Floor accelerations are low because these buildings are not likely to resonate with the ground motion. Whatever story drift is imparted, it will be resisted by the strong, yet flexible, lateral force-resisting

system. A common example of this construction are tall, modern buildings founded on rock.

FLEXIBLE LIMITED-STRENGTH STRUCTURES

These structures may not respond significantly to the earthquake but because of their weakness, may become unstable at large storey drifts. An example of such behaviour is a residential house with a large ground floor garage. Typically, the first storey is flexible and has very limited strength. Numerous houses and apartments in the Los Angeles area failed during the Northridge earthquake due to this 'soft-storey' collapse mechanism.

PROTECTED SYSTEMS

Structures utilizing this approach are becoming more common and include both passive or active protective components designed to modify the response of the building to ground motions. The active systems adapt their properties to the earthquake response of the structure in order to mitigate harmful effects of the shaking. Examples are tuned-mass dampers, magnetic rheological dampers, and stiffness-control devices. These systems require complex controls and a secure source of power, which makes them both sophisticated and expensive. On the other hand, passive systems, are often simple replaceable devices inserted into the structural system with the purpose of absorbing deformations and energy during seismic shaking. Passive systems include assemblies which are made flexible by setting the superstructure on rubber or friction isolators, and systems with artificially increased damping through the use of viscous, friction, or hysteretic dampers. These systems are detailed in this report .

3.2 Wood-Frame House Response to Earthquakes

The primary component providing lateral-load resistance in a framed house is the shear panel. Two types of shear panels are found in a typical house: horizontal diaphragms forming the floors and vertical shear walls between openings in the exterior walls. In both cases, the panels consist of framing (floor joists or wall studs) covered with sheathing (plywood, oriented strand board panels, and gypsum drywall panels).

An example of laboratory test results of such a shear panel under seismic load are shown in Figure #4, on the next page, which describes the lateral load-deformation curve of a non-engineered OSB panel with dimensions 2.4 m x 2.4 m and subjected to a simulated earthquake

Point A in the Figure indicates the initial state of the panel with zero deflection and zero load. Point B is the estimated yield point. The slope of line AB is the initial stiffness of the panel. Following yield at point B, the stiffness decreases significantly. At point C, deterioration of strength starts, leading to point D with significantly diminished resistance. It can be seen that the force-deformation - or hysteresis - loops are 'pinched' towards point A. This is an indication of a 'slack' in the system, as fastener holes are torn larger and fasteners are pulled out of the material. At the end of the test, this particular panel reached a state with very little resistance (curves along line DA), a permanent offset of about 60 mm, and severe damage throughout the panel with failed nails and screws plus sheathing which is partially separated from the frame. If a similar panel is used in a building, the panel maximum deformation and the number of cycles of deformation will determine the damage level suffered by the structure.

The typical, well-designed, wood-frame house belongs to the 'Rigid Limited-Strength Ductile' category. The primary rigidity of the structural system with its diaphragms and shear walls is compounded by secondary non-structural rigidity of gypsum wallboard panels on both the exterior walls and partitions, as well as windows, doors, exterior cladding, etc. As the building deforms during an earthquake, the system softens by quickly incurring damage to the more brittle components, especially gypsum wall board panels. As the building undergoes repeated cycles of deformation, the load resistance of the shear panels degrades as nails fail in fatigue, pull-out or tear-through.

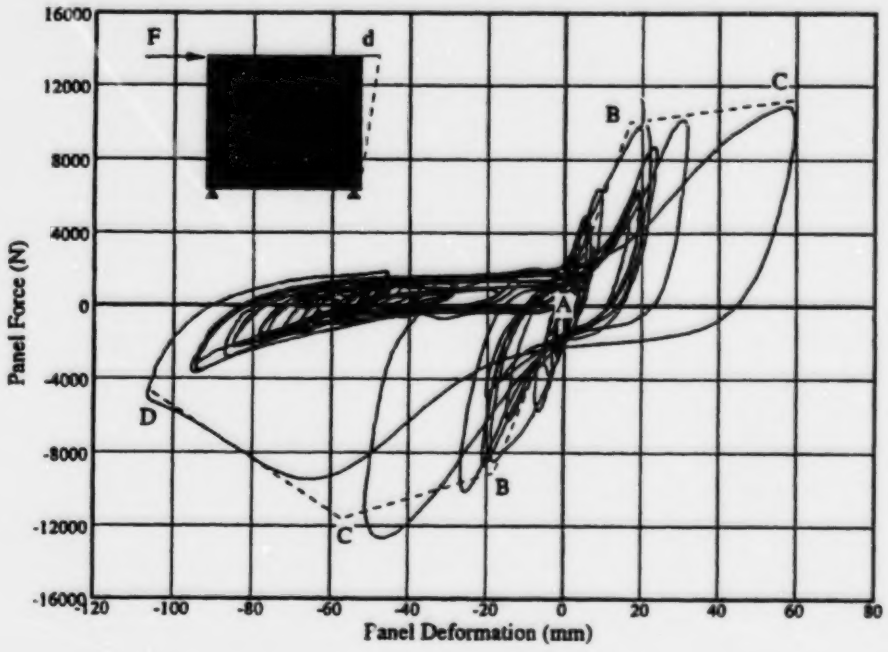


Figure 4 : Example of a Dynamic Load Deformation Curve of an OSB Panel [10]

However, due to a redundancy inherent in wood framing with its many individual panels and many fasteners in many studs, the well-designed framed house is unlikely to lose enough of its resistance to collapse even under a large earthquake.

3.3 Past Performance

The most recent major earthquake in Japan affecting a densely populated area occurred in Kobe on January 17, 1995. The satisfactory performance of wood-frame, North American style houses was in sharp contrast with the performance of the conventional Japanese post-and-beam houses whose collapse accounted for the majority of over 5000 deaths in that earthquake [14]. There are other factors aside from construction type that have contributed to this outcome, however, it was apparent that the wood-frame houses satisfied the intent of the codes by preventing collapse and allowing the safe escape of the occupants. The Kobe event could be classified as somewhere between a moderate and a severe earthquake depending on the location within the affected area.

A year earlier, in the Los Angeles area in California, a large inventory of wood structures were subjected to the magnitude 6.5 Northridge earthquake with peak ground accelerations of 0.6 g or higher in some areas. The performance varied greatly depending on the type of house under consideration [13]. Many houses with large parking garages on the ground floor showed a 'soft storey' behaviour and suffered serious damage and collapse in some instances. In other instances, discontinuous load paths were the cause of severe damage to wood houses, drawing attention of designers and inspectors to detailing for continuity. In addition, some experts pointed out that many wood-frame structures survived only due to the type of ground motion produced by this event, in which a single large impulse was followed by low

intensity shaking. It has been argued that many more buildings might have collapsed if the same high-intensity shaking had continued for a few more cycles.

3.4 Earthquake Loads in Japanese Building Codes

There are two codes governing the design of buildings in Japan [2] [5] which designate two levels of earthquake loads with their corresponding performance levels - a moderate earthquake and a severe earthquake, with typical levels of maximum ground acceleration of 0.2 g and 1.0 g, respectively. A building is expected to survive the moderate earthquake with minimal damage and the severe earthquake without collapse.

For wood buildings up to three storey high, the code do not require that the building be designed for the severe earthquake. It is not even necessary to perform structural design calculations if the building is regular in shape and complies with standard construction and detailing requirements. A similar provision for small wood-frame buildings is found in the Canadian codes [6] [7].

3.5 Expected Performance

If the Japanese code philosophy is projected onto a wood house, the house should endure the more frequent moderate earthquake with peak ground acceleration of 0.2 g, with minimum damage and the rare severe earthquake at 1.0 g without collapse. As discussed in 3.2, a well-designed wood-frame house should be able to meet these performance criteria.

However, it became apparent after the Northridge and Kobe earthquakes, that **the public has a different expectation of the appropriate seismic performance of buildings**. What a building official or an engineer might have called a satisfactory performance, became a disaster to the financial well-being of the individual, business, or community. The damage in Northridge was in the tens of billions of dollars, while the casualties were in dozens. In Kobe, the damage was in the hundreds of billions of dollars, while the majority of the 5,500 casualties occurred in the poor section of the city with code non-compliant, post-and-beam houses with heavy tiled roofs. As a result, in post-Kobe Japan, the demand for protected buildings, that stand a good chance of being functional following a major earthquake, has risen dramatically. According to current surveys, the number of base-isolated residential apartment buildings constructed annually since 1995 is rising exponentially.

Seismic isolation seems to be the dominant feature in advertisements for apartments in buildings with such systems, indicating that the Japanese buyer understands and appreciates the benefit derived from a protective system. In a parallel development, the demand for framed houses has also risen due to their good earthquake performance.

There are many North American contractors and construction workers building framed houses in Japan. In this climate, it is natural to consider the provision of a package that includes both the framed house and a seismic protective system. The Canadian Home Concept intends to provide such a solution.

CHAPTER FOUR: PASSIVE PROTECTIVE SYSTEMS

Passive protective systems fall into two primary categories: base isolation systems or damping systems.

4.1 Seismic Isolation Systems

The objective of base isolation systems is to decouple the building from the ground motion by inserting a flexible isolating plane between the ground and the structure. In simple terms, the building rides out the earthquake without responding significantly, while the isolation plane takes all of the deformation. The principle is illustrated in Figure 5. The isolation system must be flexible enough to achieve good isolation, yet it must be sufficiently stable to carry the gravity loads in its displaced position. It is further desirable to have a significant damping presence to further decrease the response.

Rubber Bearings

Rubber bearings are the oldest isolation devices in use. Some bearings have been in service for over a hundred years in bridge applications, although they were not installed as seismic isolators but rather as expansion bearings. Modern rubber bearings consist of several layers of natural rubber or neoprene alternating with thin steel plates all bonded together as shown in Figure 6(a). The important property of rubber bearings is their lateral flexibility combined with high vertical stiffness. This makes them ideal for isolation purposes where they must be able to carry vertical gravity loads but isolate the building from damaging horizontal earthquake motions.

Lead-Rubber Bearings

Lead-rubber bearings, Figure 6(b) are rubber bearings with a lead core inserted in the centre. The lead core makes the bearing stiff under wind and service loads. In earthquake, the lead core yields and provides additional hysteretic damping to the system.

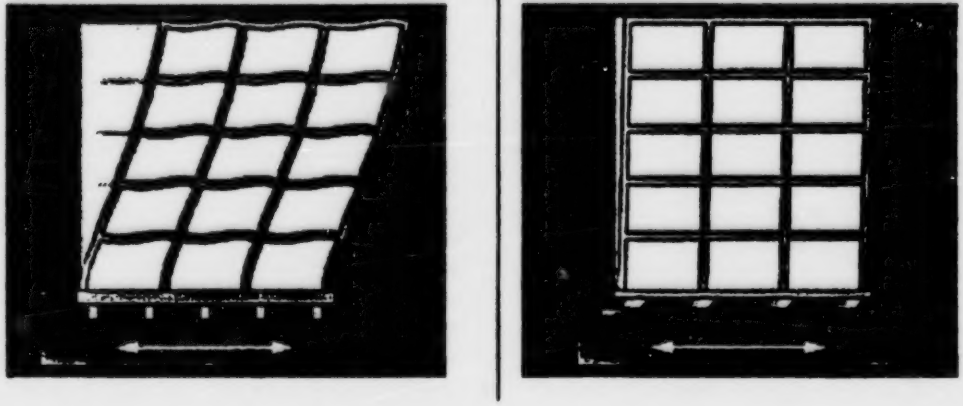


Figure 5 [a] Non-isolated Building Response [b] Isolated Building Response (DIS Inc.)

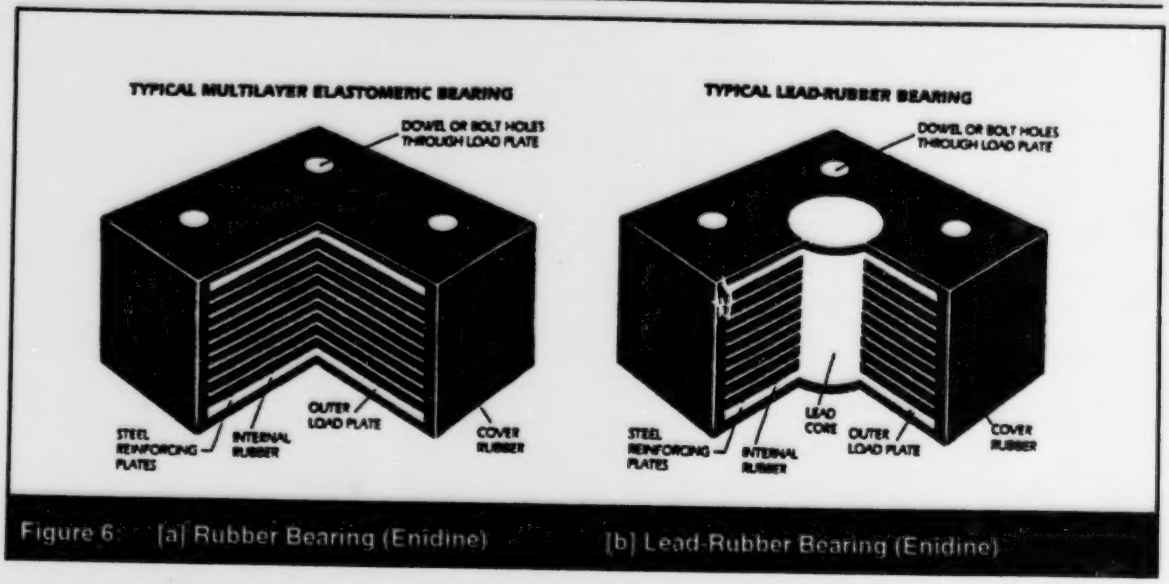


Figure 6: [a] Rubber Bearing (Enidine) [b] Lead-Rubber Bearing (Enidine)

Flat Friction Sliders

Friction sliders begin to move when the lateral load exceeds the friction force on the slider. Friction force depends on the vertical force or gravity load on the slider. During sliding, the friction force is constant or varies with the velocity of sliding, depending on the contact materials. Typical materials used are teflon sliding on a stainless steel plate with a resulting coefficient of friction between 8% and 12%. A typical flat slider is shown in Figure 7(a).

Friction Pendulum Sliders

A friction pendulum slider, shown in Figure 7(b), is a slider whose friction surface is curved. As the slider moves, the resisting force increases as the surface becomes more inclined. And inversely, a smaller force is required to return the slider to its central and lowest position. Consequently, the maximum displacement during an earthquake of the isolation system is decreased, as is the permanent offset following the earthquake.

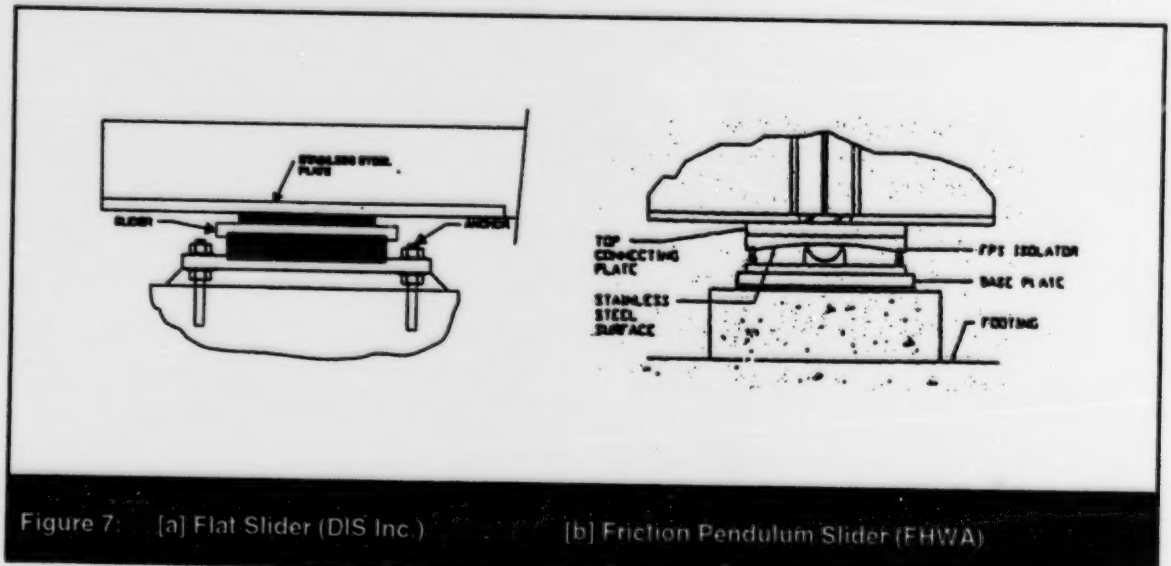


Figure 7: [a] Flat Slider (DIS Inc.) [b] Friction Pendulum Slider (FHWA)

Other Isolation Systems

Many other isolation systems have been studied and some implemented. Examples are building sitting on a pea gravel bed, buildings on rollers, building on a layer of chalk, suspended buildings, and others. While some of these concepts would be significantly cheaper than engineered devices such as lead-rubber bearings, their effectiveness, durability, and reliability would be difficult to establish. As the Canadian Home Concept requires a system that would gain acceptance in an advanced and sophisticated market, it is advantageous to focus on systems which have been accepted for other application.

4.2 Energy Dissipation Systems

Energy dissipation systems try to funnel the kinetic energy imparted to the structure by an earthquake into special devices which have been installed in the structure.

Viscous Dampers

Similar to automobile shocks, viscous dampers dissipate energy by pushing viscous fluid through a small orifice within a sealed vessel. The faster the rate of movement, the more force is required and the more energy is converted into heat in the fluid.

In order for these devices to work, they must be installed between two points that will move against each other during an earthquake. It is common to insert them in secondary diagonal bracing in steel structures. Figure #8 [a] shows viscous dampers.

Friction Dampers

There are several types of friction dampers available on the market. Some of these are similar to viscous dampers in that they have the shape of a sealed cylinder with a shaft pulling and pushing against a series of friction rings and springs. Other devices are designed specifically for steel braces and have the form of steel plates pressed against each other by pre-tensioned bolts. In both types of devices, sliding occurs when pre-determined friction force is exceeded. As the device is stretched and compressed repeatedly, kinetic energy is converted into heat.

Hysteretic Dampers

Hysteretic dampers dissipate energy by bending specially shaped rods, plates or other steel elements. As with all protective systems, they must be placed so that the structure 'works' or 'deforms' the device. A hysteretic damper is shown in Figure 8(b)

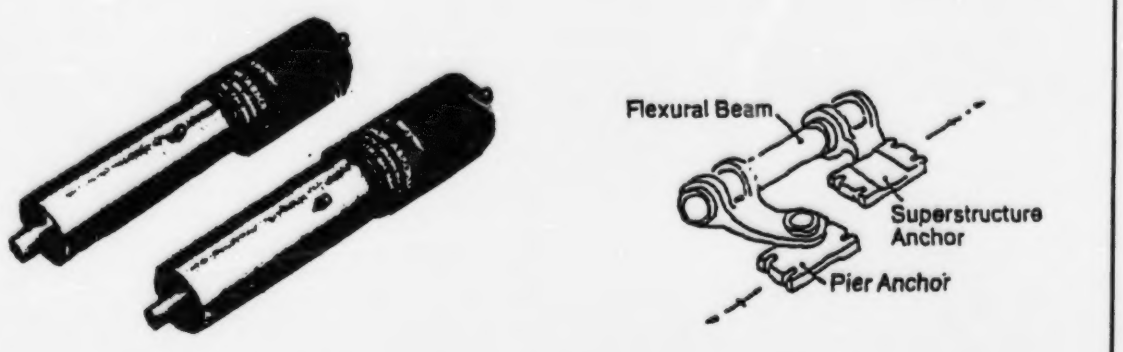


Figure 8 [a] Viscous Damper (Taylor) [b] Hysteretic Damper (FHWA)

4.3 Selection Criteria

To select an appropriate system for the Canadian Home Concept, it was necessary to establish a set of criteria and performance characteristics required of the system. These included:

- EFFECTIVENESS - The system is to protect the house from seismic shaking by limiting floor accelerations and storey drifts under severe earthquake thus leaving the post-quake home 'functional'. The system also must prevent excessive displacements under wind and service loads.
- SIMPLICITY - ease of installation, maintenance, durability, inspection, plus allowing for addition to the house, etc.
- COST must be kept at a reasonable proportion to the cost of a residential house. A working figure for the entire protective system was C$15,000.
- ACCEPTANCE of the system by regulatory bodies and the public.

4.4 Selection of a Protective System

An elimination approach was taken during the selection of a protective system.

Dampers

The systems with various dampers installed within the building, did not meet several of the acceptance criteria as detailed in Table 1, below. The main shortcoming of dampers installed within the structure lies in the requirement that the building repeatedly deform significantly in order to work the device. In case of the framed house, this would lead to significant damage to drywall and interior finishes. Further, these devices would have to be concealed in walls, which is typically not acceptable, as inspections are a regulatory requirement. This led to focussing on isolation techniques.

Isolation

The obvious location of the isolation plane is at the foundation level, with the house set on top of the isolation devices. However, in the case of the RORO house, it was found that the weight of the house was insufficient for an isolation system to work effectively without allowing excessive displacements under wind and service loads. As shown later in the analytical part of this report, the design wind force on a house in Japan can be up to 30% of the weight of a framed house. An isolation system that would resist this load without significant deformation, would not be effective in an earthquake.

Table 1 Dampers - Selection Criteria Rating

Criteria	Compliance	Rating
Effectiveness	Dampers increase the dampening of the system and thus decrease the seismic response. However, damage could not be prevented because the devices require significant deformation to occur	Unsuitable
Functionality	Installation in walls would prevent access for inspection and testing. Further, a new, additional structural system would have to be incorporated into the framing system.	Unsuitable
Cost	Cost is high with small seismic dampers in the range of $10,000 each.	Unsuitable
Acceptance	Dampers are a proven technology.	Suitable

The target trigger load should be at about 10% to 15% of weight of the structure. One solution is to increase the weight of the building by setting it on top of a concrete slab above the isolation plane. The systems discussed below assume this case.

Rubber and Lead-Rubber Bearings

Rubber isolators would have to be unusually flexible to isolate a structure this light even with the added slabs. Given this flexibility, they could not prevent significant displacements under wind load. Rubber bearings with lead cores could be designed to resist the wind loads without yielding, by making the lead cores sufficiently large. It was found, however, that lead-rubber bearings with sufficient flexibility were not stable under the large displacements expected during a severe earthquake. In addition, the need to concentrate the largest possible gravity loads into as few units as possible, lead to a design with widely spaced units. This posed a problem in the design of the concrete slabs. The selection criteria rating for lead-rubber bearings is shown below in Table 2.

Sliders

With the elimination of rubber and lead-rubber bearings, the study's focus shifted to friction-based isolators. A teflon-steel slider has a friction coefficient between 10% and 12% at design velocities. With the increased weight of the building, the slider could effectively prevent displacements under low wind storms. It was, however, necessary to prevent large displacements under the design wind load which still exceeded the friction force. Also it is a requirement of most design codes, that a returning or centering force must act on the displaced isolated structure during seismic attack. Flat sliders by themselves could not satisfy the performance criteria.

Friction Pendulum Sliders

The code required centering force noted above could be obtained by the use of a friction pendulum slider. However, while this system offers a significant returning force, its sophistication over a flat slider suggests prohibitive costs.

Combination System with Flat Sliders and Friction Dampers

A study was conducted on the effectiveness of a system in which a set of flat sliders was combined with a set of SHAPIA friction dampers at the isolation plane [8]. This system has proven to be quite effective in reducing the floor accelerations and storey drifts. However, the cost of the dampers was prohibitive.

Table 2 Lead-Rubber Bearings - Selection Criteria Rating

Criteria	Compliance	Rating
Effectiveness	Sufficiently flexible bearings would be effective in protecting the house. However, with such flexible bearings, instability problems occurred under large displacement expected during severe earthquakes.	Unsuitable
Functionality	The bearings can be easily installed, inspected and replaced if necessary without disturbing the interior functions or finishes.	Suitable
Cost	Cost is reasonable, in the range of $20,000 for four bearings plus the concrete work.	Suitable
Acceptance	Lead-Rubber bearings are a proven technology.	Suitable

Combination System with Flat Sliders and Rubber Springs

This system combines a set of friction sliders with several rubber bearings, acting as linear springs. The friction sliders support all the gravity load and provide isolation through friction sliding. The rubber springs do not support any gravity loads but rather provide a centering force opposing the displacement of the superstructure. This system, with selection criteria rating listed in Table 3, was selected as the recommended solution and a specific design of such a system is described in the next section.

Table 3 Slider Spring Systems - Selection Criteria Rating

Criteria	Compliance	Rating
Effectiveness	Effectively decreases the seismic demand on the wood frame by allowing the superstructure to slide on the foundation. Linear springs limit displacement and provide a restoring force.	Suitable
Functionality	All devises are installed externally enabling easy inspection, have a low requirement for maintenance, are durable and reliable. Excessive displacement under wind and service loads is prevented by the addition of concrete slabs.	Suitable
Cost	The total cost of the sliders and springs is estimated at $15,000 per home which is the lowest cost of all the special-device solutions considered in this project. Concrete foundations and slabs are in addition to this cost.	Suitable
Acceptance	Both sliders and springs are proven technologies.	Suitable

CHAPTER 5: PROPOSED PROTECTION: SLIDER-SPRING SYS.

5.1 General Description

The hybrid slider-spring system proposed for the protection of the Canadian Home Concept is shown on the following pages and described here in detail.

The solution presented is one of many possible configurations for the typical 6-module house, but full optimization of the design was beyond the scope of this preliminary study. In this design, 8 sliders supporting three precast concrete slabs. The housing modules are in turn mounted and attached to the top of those slabs. Four linear shear springs are located close to the four corners. A detailed description of the components follows.

5.2 Foundations

The sliders and linear springs can be mounted on practically any type of foundation, including:

- spread footings under the isolators
- a foundation slab with thickenings under isolators
- piles under the isolators.

The system is expected to be relatively tolerant to differential vertical and lateral settlements under normal service conditions. However during seismic attack, it is necessary to ensure that the support points maintain their relative positions. For example, if the site has a potential for liquefaction, then even if piles are used as a foundation system, there is a good chance that the pile caps will move relative to each other unless prevented from doing so. It may, therefore, be necessary under some soil conditions to construct a grid of grade tie-beams between the pile heads.

The proposed clear height of the crawl space is 200 mm which is to be screened by a break-away skirting designed so as not to resist the movement of the isolation system. The bottom of the crawl space is covered either with gravel, sand or slab on grade in response to market conditions. Drainage is required to accommodate any intrusion of groundwater and where climatic conditions dictate, insulation is provided along the skirting.

5.3 Sliders

The slider shown in Figure 9 is a flat elastomer-backed sliding isolator. It consists of a base plate, a layer of elastomer, and a steel plate with a sliding surface. The elastomer layer, typically neoprene, is bonded to both steel plates. It provides an initial flexibility to the system reducing the transmission of high frequency earthquake vibration to the building. Its thickness relative to the plan dimensions of the slider determines the stiffness of the device before sliding. It can be adjusted to provide an optimum performance under both wind and earthquake conditions. The sliding surface is made of PTFE (polytertafluoroethylen) or teflon bonded to the lower steel plate. The coefficient of friction for these materials in combination with polished stainless steel varies with pressure and velocity, with typical values shown in Table 4.The slider is attached to the concrete footing using four anchor bolts.

Table 4: Coefficient of Friction Values

	Low Velocity	High Velocity
Teflon/Stainless Steel [3]	0.06-0.08	0.12-0.14
PTFE/Stainless Steel [9]	0.03	0.12-0.15

5.4 Stainless Steel Plates

The slider described in 5.3 bears against a stainless steel plate cast in the upper concrete slabs. The steel plate must be large enough to provide support in the range of expected movement of the slider. It has an added function in the current design, and that is to provide a connection between the slabs. The thickness of the plate is governed by the two functions and by fabrication details, such as welding of headed studs to the top side. The headed studs provide a positive connection to the concrete slabs. As shown in Figures 10-12, the sliders and plates are placed under joints

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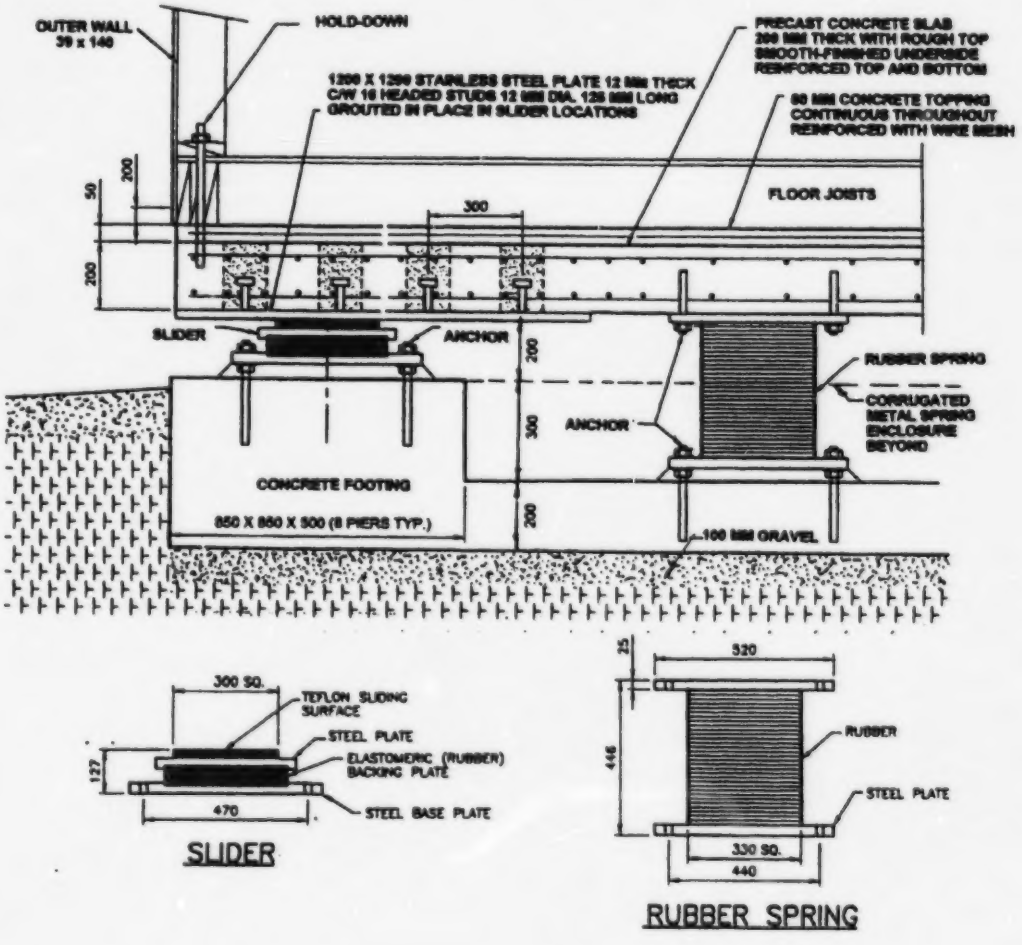

Figure 9 : Proposed Earthquake Resistant Slider and Spring Details

between slabs and at the perimeter corners of slabs. The eight sliders are identical.

5.5 Linear Shear Springs

The shear springs provide a centering force opposing the displacement of the slider. This action limits the movement of the isolated building during an earthquake and minimizes any permanent offset. The springs also limit any displacement during extreme windstorms wherein the wind forces exceed the restraining friction of the sliding system.

As mentioned previously, the shear spring does not carry any vertical load and therefore does not need to be vertically stiff, unlike typical rubber bearings. This is reflected in the construction of the shear spring which does not include steel shim plates between layers of elastomer. Further, the spring has no stability limits on its plan dimensions. The only limitations are the maximum shear strains that can be safely sustained by the elastomer.

The shear springs are anchored to the foundations and to the slabs, using anchor bolts with special detailing, as shown in the drawings in Figure 9. Four identical springs are required for each house, placed as close to the four corners of the plan as possible to minimize torsional effects of the system response. It is anticipated that one size of spring will be used for all Canadian Home Concept houses, thus maximizing the benefit of economies of scale.

5.6 Concrete Slabs

The concrete slabs will be prefabricated in a specialized casting plant. The slabs are generally the same size, dictated by the dimensions of the modules. A typical slab is approximately 2.9 meters wide by 8.0 m long. A uniform thickness of 200 mm gives sufficient weight increase to prevent excessive displacement under wind load. The casting plant will be able to use a single casting bed. Detailing will vary, making each slab unique. It will be necessary to supply the casting plant with a detailed shop drawing for each slab, showing reinforcement, edge connection details, cast-in metal components, block-outs for headed studs, block-outs for services, etc.

Following placement, the slabs will be secured together by grouting the stainless steel plates in position, and by means of spot welded connections provided along the adjoining edges.

There are two ways of dealing with the deflection of the slabs under their own weight:

- Provide the slabs with a camber by pre-tensioning them, as is routinely done in the casting plant for other precast concrete elements. This method would increase the cost of the slabs, but minimize site work.

- The other way is to let a conventionally reinforced slab deflect, and then pour a level concrete topping. This would require some careful work on site so that the cast-in components of the slab remain functional. The added advantage of this solution is seen in the topping tying the slabs together in a single unit. To achieve this, the topping would have to be reinforced with a welded wire mesh.

A careful analysis is required of the behaviour of the slabs before, during and after construction, as well as during an earthquake, so that all possible loading conditions are accounted for.

5.7 Modules

The building modules are placed on top of the finished slabs and secured with hold-downs ties. The hold-downs can be of several different types, depending upon design and contractor preferences.

Options include:

- Bolts threaded into cast-in inserts. This would minimize the component of site labour, however, a careful coordination would be required between the module manufacturer and the casting plant so that the inserts align with access holes in the modules. Also, additional hardware would need to be pre-fabricated and shipped to the casting plant.

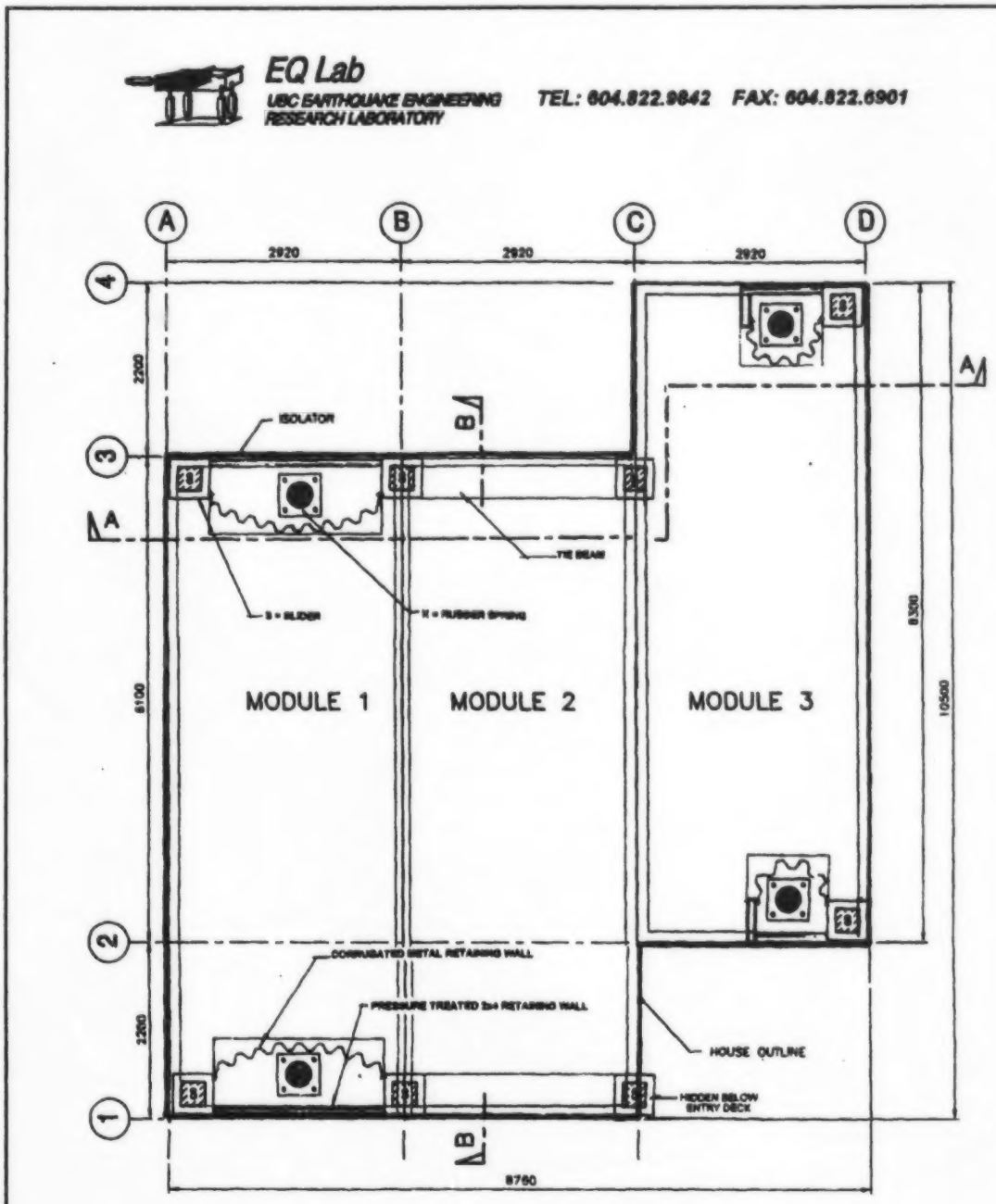

Figure 10 : Seismic Resistant Foundation Configuration - Plan

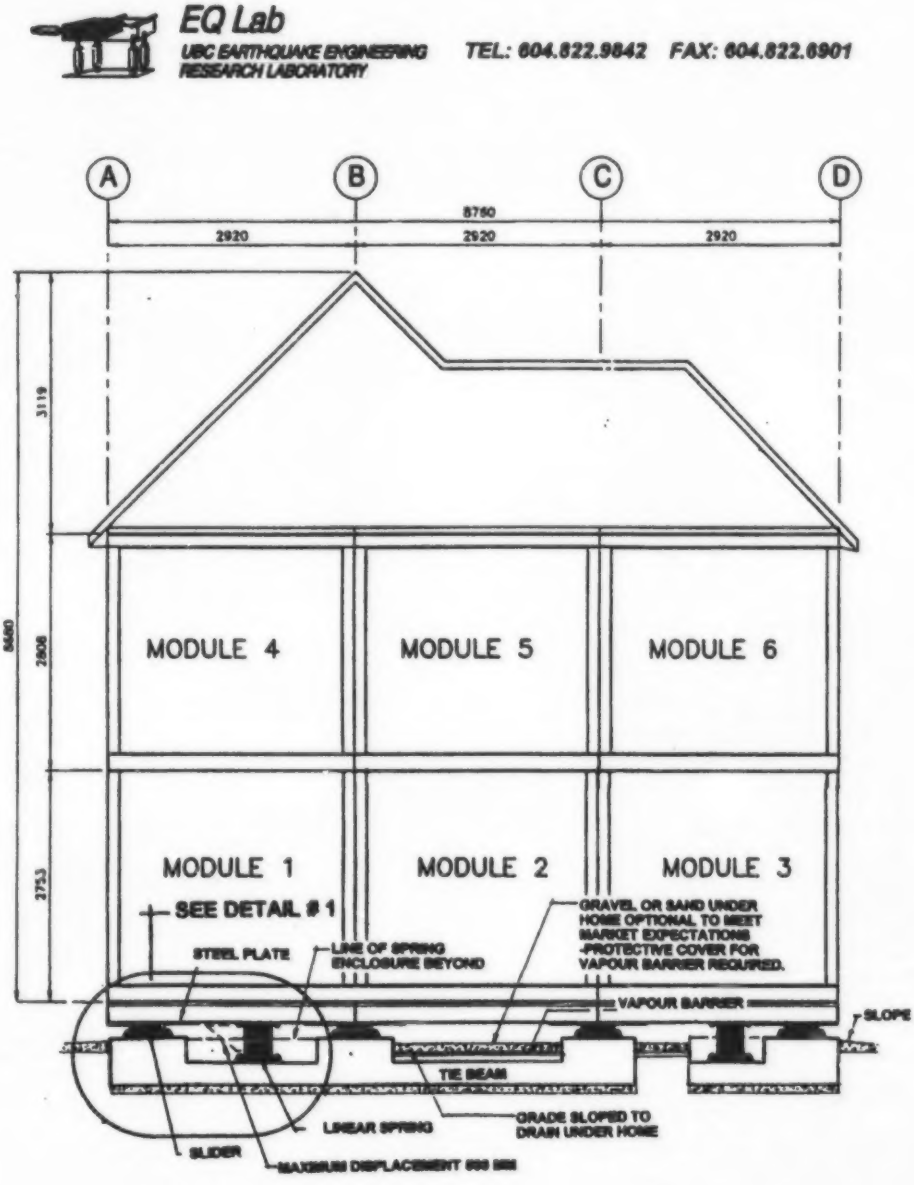

Figure 11: House Section "A" - Showing Earthquake Resistant Foundation System

- Bolts/rods anchored using chemically bonded system, such as Hilti Hit or Sikadur. This would enable the contractor to match the hold-down locations with the modules, but would require site drilling and preparation.

- Through-bolts to the underside of slabs. This solution would require the casting plant to provide carefully placed tubes through the slab along the perimeter of the slabs. This solution would conflict with sliding plates in the locations of sliders.

The modules need to be of good quality construction for even an isolated home is likely to be subjected to considerable wind and earthquake forces. Therefore, it is necessary to pay close attention to the design of shear wall panels and the connection details between modules all of which can be achieved utilizing conventional engineering, materials and construction techniques.

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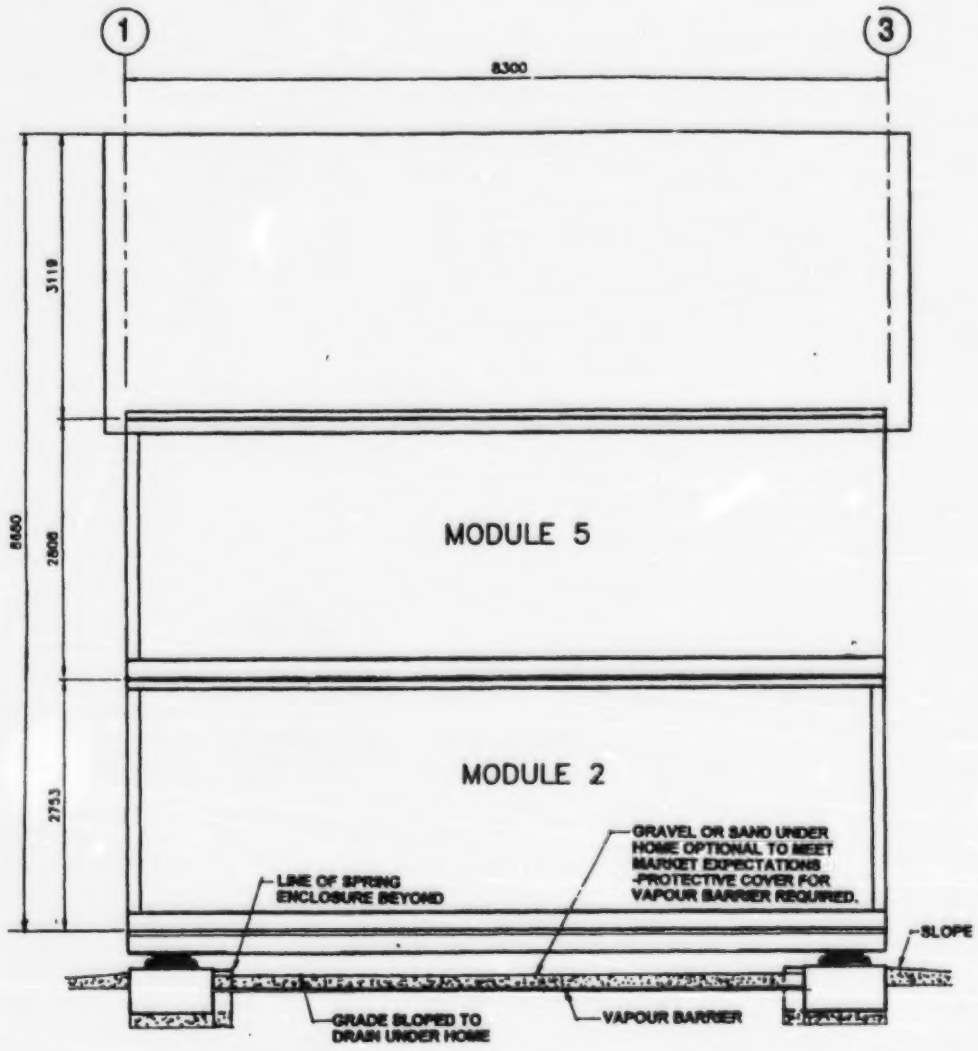

Figusre 12 : House Section "B" - Showing Earthquake Resistant Foundation System

CHAPTER 6: ANALYTICAL VERIFICATION

The objective of the analytical verification was to demonstrate the effectiveness of the isolated system in protecting a modular Canadian Home Concept structure and its contents under a seismic attack.

6.1 Seismic Weight

The weight for consideration in seismic design included self-weight of the modules and the concrete slabs, as well as contributions from partial live and snow loads. The modules weigh about 4,000 kg each [1], giving a total of 24,000 kg (235 kN) for six modules. The Japanese Building Code [2] requires that a small portion of live load be incorporated in the seismic design calculations. This load is set at 60 kg/m2 (0.59 kPa). For six modules with area of 139 m2, the total contribution from live load is 8,300 kg (81 kN). A further increase of weight is due to snow load, which will vary depending on the location of the house. A typical value of 200 kg/m2 was considered a reasonable estimate of roof snow load, of which 25% is to be included in seismic calculations [2]. This increases the weight of the system by another 3500 kg (34 kN).

NOTE: *Snow loads are not utilized in the subsequent discussion of the apartment building in order to consider that option from the broadest geographic perspective; including warmer southern Japanese locations. Further, there has been no load included for any roof structures as they can vary considerably by location and this approach is not influenced by that element.*

The total seismic weight of the house without the concrete slabs is, therefore, 35 800 kg (351 kN) The three concrete slabs with dimensions 2.9 m x 8.0 m x 200 mm add 33,400 kg (328 kN) to the system, to a total weight of 69,200 kg (679 kN).

6.2 Analytical Model

A simple two-dimensional, finite element model was build using structural analysis program SAP 2000 Nonlinear [15]. The model, which is schematically shown in Figure 13, simulated the behaviour of one half of the building in section perpendicular to the long dimension of the modules. This was considered the more critical section.

The model consisted of two storeys 3,000 mm high with three bays 3,000 mm wide, approximately corresponding to six modules. A roof structure formed the third level. The horizontal and vertical links were rigid frame elements. Each frame was supported laterally with a diagonal brace. Concentrated masses were located in joints with magnitudes calculated from estimated component weights. The total weight of the model was 33,000 kg (332 kN), corresponding to half of the building.

Diagonal Braces

The diagonal braces on the first and second storeys were modelled using nonlinear plastic elements Plastic1, while the bracing at roof level consisted of regular frame elements. The nonlinear plastic elements had an initial stiffness, yield force and post-yield stiffness corresponding to the combined effect of partial plywood shear wall panel on the exterior of the house with gypsum wall board sheathing on the inside as well as on partitions. The combined resistance and stiffness was obtained from experiments reported in the available literature [10]-[12]. It was assumed that the framing was of 2x6 construction with panelling oriented horizontally, and the exterior wall fully blocked for maximum resistance. The initial stiffness of the panels was assumed to be high, as was observed in experiments. A typical set of brace element properties is shown in Table 5, and Figure 14.

The SAP nonlinear element is not capable of modelling the deterioration of strength at large deformations or with increased number of cycles of deformation. However, it was deemed unnecessary for this project, as the objective was to show that the shear walls were protected to a level below deterioration levels.

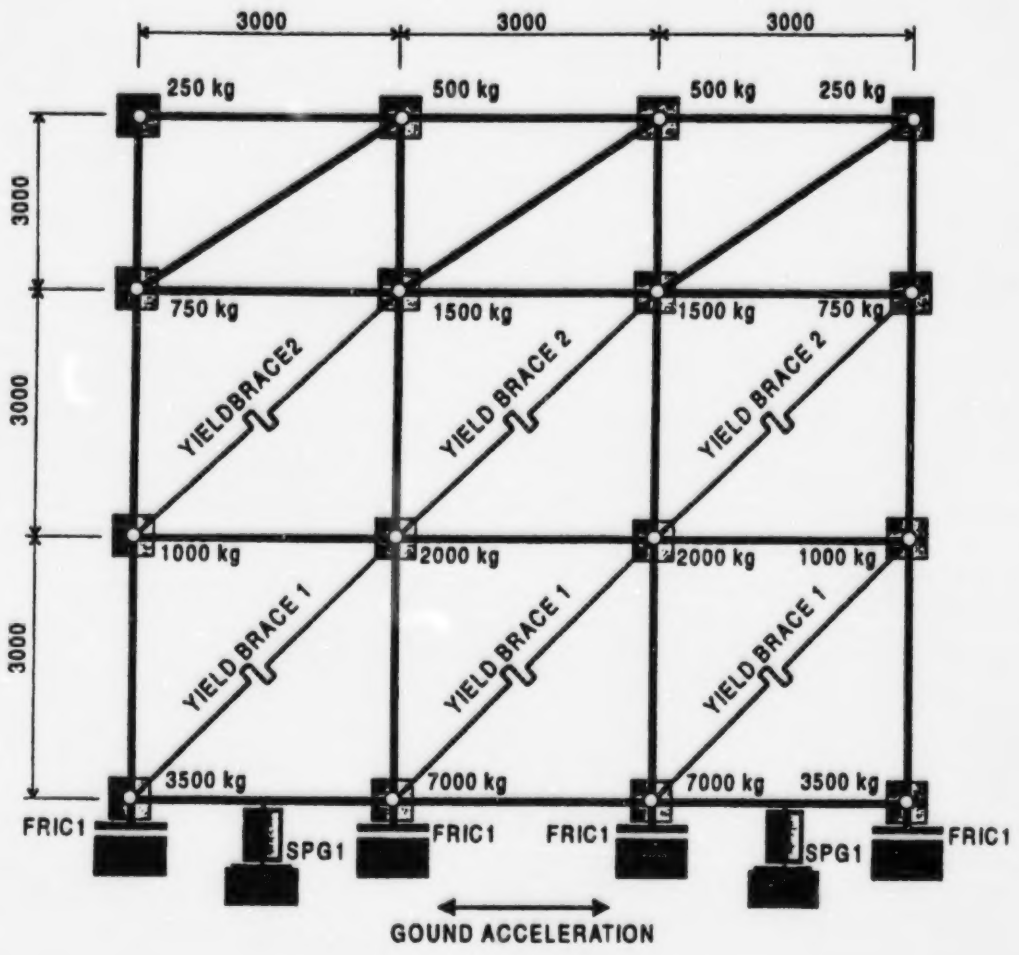

Figure 13 : SAP2000 Wire Frame Model of 2 Storey Home Used in Verification Study

Table 5: Properties of Brace Elements

	Property	Brace Axial	Effective Horizontal
FIRST STOREY	Initial Stiffness	1500 kN/m	750 kN/m
	Yield Force / Deformation	Fb=30 kN @ db = 20mm	Fh=21 kN @ dh= 28mm drift
	Post Yield Stiffness	315 kN/m (21% of initial)	158 kN/m (21% of initial)
SECOND STOREY	Initial Stiffness	1250 kN/m	625 kN/m
	Yield Force / Deformation	Fb=25 kN @ db = 20mm	Fh=18kN @ dh= 28mm drift
	Post Yield Stiffness	263 kN/m (21% of initial)	132 kN/m (21% of initial)

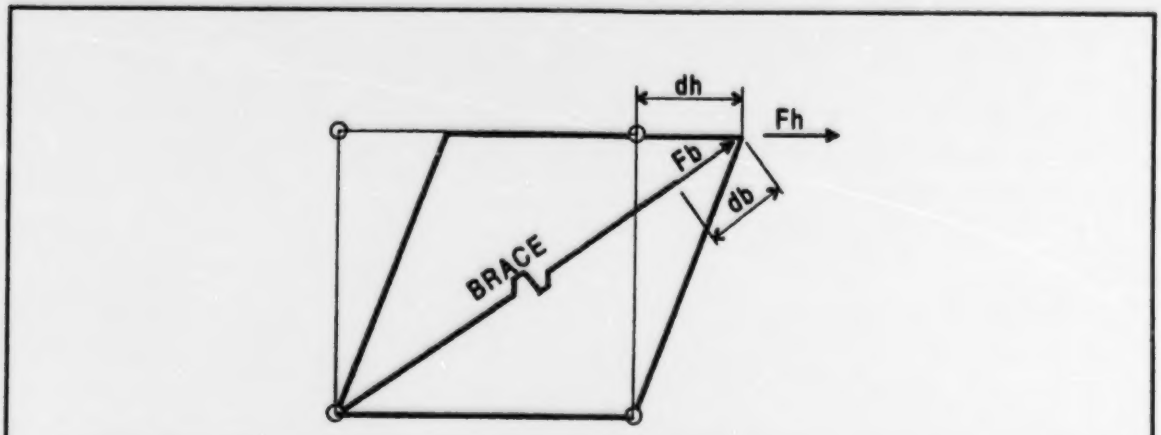

Figure 14: Panel Forces and Deformation

Table 6 : Properties of Slider Elements

Property	Value
Vertical Stiffness	44,000 kN/m
Horizontal Stiffness	2,280 kN/m
Coefficient of Friction- Low Velocity	0.07
Coefficient of Friction - High Velocity	0.13
Hysteretic Parameter	1.0
Radius of Friction Surface	100 m (= flat)

Sliders

The sliders were modelled using SAP nonlinear element Isolator 2. This element represents a friction slider with a curved or straight friction surface. The properties used for the model (see Table 6), are based on recommendations by Dynamic Isolation Systems Inc. of California [3].

Linear Shear Springs

The shear springs were modelled using the SAP nonlinear element Isolator 1 with the nonlinear properties turned off. The advantage of using the nonlinear element rather than a regular spring, was in being able to output more information about the element behavior both graphically and numerically in the SAP Postprocessor. Further, it was possible to experiment with various levels of damping and nonlinearity during the optimization stage of the project. The linear properties used for the shear springs are given in Table 7

Table 7 : Properties of Spring Elements

Property	Value
Vertical Stiffness	78 kN/m
Horizontal Stiffness	78 kN/m

6.3 Earthquake Loading

Three earthquake motions were applied to the model. The earthquakes were selected from a wide range of types to investigate the applicability of the design to varying conditions. A summary of earthquake records is provided in Table 8.The records were later amplified by scaling up to a peak ground accelerations in the range of 0.8 to 1.1 g corresponding to a 'severe' earthquake level of the Japanese building code.

Table 8 : Earthquake Records Used in Analysis

	Earthquake	Peak Ground		Duration of Strong Shaking
		Acceleration	Displacement	
1	Northridge , CA Earthquake -1994 Recorded - at Sylmar County Hospital	0.6g ($g = 9.81 m/c^2$)	150 mm	10 sec's.
2	Kobe-Great Hanshin Quake -1995 Recorded - at Kobe University	0.3g	200 mm	12 sec's.
3	San Fernando Earthquake - 1971 Recorded - at Pacoima Dam	1.2g	370 mm	10 sec's.

6.4 Results

The model was analyzed under two conditions: a FIXED model with the isolation disabled, and an ISOLATED model. The fixed model did not have the benefit of the isolation system and transferred earthquake loads directly to the structure. The parameters selected for describing the performance of the isolated building were:

- Base Shear is the maximum horizontal reaction exerted by the structure on its base. The objective of the isolation system is to minimize base shear.

- Floor Accelerations are a measure of inertia forces experienced by the superstructure. High floor accelerations have a damaging effect on the contents of the building.

- Storey Drifts indicate the level of structural damage sustained by the building.

- Isolator Displacement indicates the amount the isolator displaced during the event. Both maximum and permanent displacements were recorded.

The results are reported in a tabular form on the following pages in Tables #9 through #14 inclusive.

Northridge Earthquake

Table 9 : Northridge Record : Amplified Input Parameters Used for Simulation

Input Parameters	Value
Scale From Original Record	1.5
Peak Ground Acceleration	0.9 g
Peak Ground Displacement	325 mm

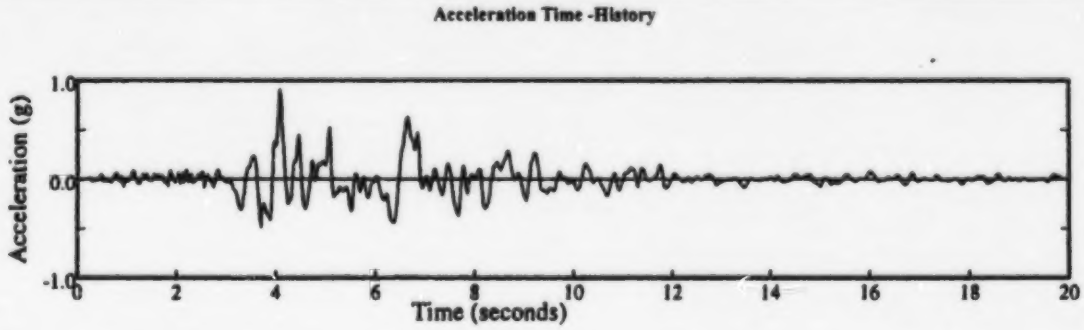

Table 10 : Northridge Record - Output Parameters from Analysis

Output Parameters		Fixed Structure	Isolated Structure	Reduction Factor
Base Shear		0.63 weight	0.21 weight	3.0
Floor Acceleration	1ST	0.90 g	0.31 g	2.9
	2nd	1.01 g	0.35 g	2.9
Storey Drift	1st	132 mm	23 mm	5.7
	2nd	45 mm	14 mm	3.2
Isolation Displacement		0	268 mm	

San Fernando Earthquake

Table 13: San Fernando Record : Amplified Input Parameters Used for Simulation

Input Parameters	Value
Scale From Original Record	1.0
Peak Ground Acceleration	1.2 g
Peak Ground Displacement	370 mm

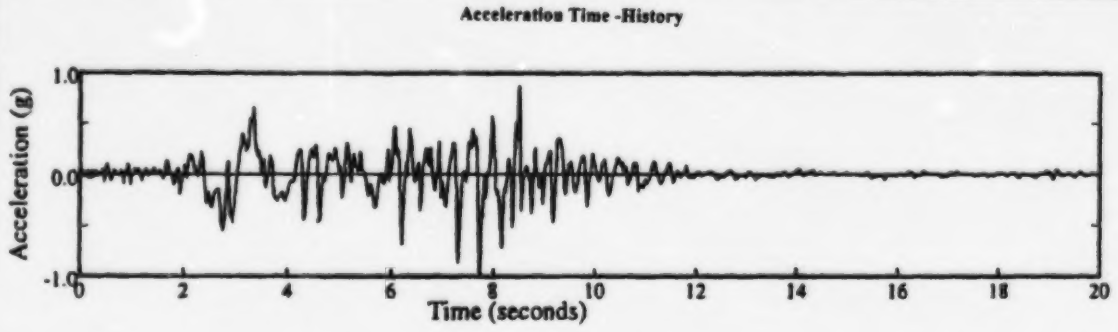

Table 14 :San FernandoRecord - Output Parameters from Analysis

Output Parameters		Fixed Structure	Isolated Structure	Reduction Factor
Base Shear		0.63 weight	0.21 weight	3.0
Floor Acceleration	1ST	1.20 g	0.43 g	2.9
	2nd	0.78 g	0.42 g	1.9
Storey Drift	1st	60 mm	41 mm	1.5
	2nd	40 mm	24 mm	1.7
Isolation Displacement		0	277 mm	

6.5 Analysis Summary

The analysis presented in this section showed that the proposed protective system would significantly reduce the forces and deformations of the structure during a severe earthquake.

Storey Drifts

The fixed model of a seismically unprotected home, showed that the lateral load-resisting system, or shear walls, would be subjected to repeated large deformations which would likely result in severe damage to the building. The effect of isolation to create a seismically protected home was decreased deformations of the shear walls to within their elastic range in most cases. Even in cases where a larger deformation occurred, such occurrence was limited to one or two excursions into the inelastic range, which was well within the estimated capacity of the shear wall system.

Figures 11 (a) and (b) show force-deformation curves for first floor panels in the fixed (non-isolated) and isolated structures subjected to the amplified Northridge record. It is apparent that the panel in the fixed structure would be severely damaged. The panel in the isolated model was subject to much smaller deformations and would likely be only lightly damaged, if damaged at all.

Floor Accelerations

The analysis showed that isolation reduced the peak acceleration of both floors. While the isolated floor accelerations are still significant, and some damage to contents of the house could occur during a severe earthquake, it would be much less even than the effect on objects lying on the outside ground.

Base Shear

The reduction of base shear is a basic measure of the effectiveness on the isolation system. In all cases, the analysis showed a significant reduction. However, it is not an indication of design loads on foundations, because the fixed model contained the concrete slab above supports, which would not be the case in practice. It is likely that by adding the concrete slabs, the foundation loads have increased as compared to a fixed structure with no slabs.

Isolation Plane Displacement

The isolation plane displacements shown by the analysis were in the order of 300 to 500 mm. This is close to the predicted levels and is accommodated in the design.

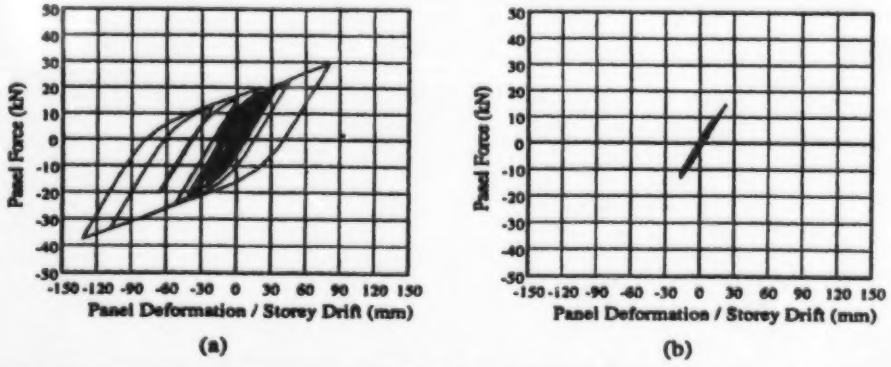

Figure 15 : Force Deformation Plots First Floor Panels During Northridge Record Analysis
(a) Fixed Structure (b) Isolated Structure

6.6 Wind Load Analysis

In order to determine the response of the seismically protected house to wind loads, a simplified analysis was performed. For the estimation of wind loads, two procedures were used with the results given in Table 15.

Table 15 : Wind Load Forces

Load Calculation Procedure	Wind Force
Building Standard Law of Japan	115 kN
Architectural Institute of Japan	91 kN

The AIJ procedure is the more sophisticated and appears more realistic of the two. It further states that the design wind loads are based on a 100 year return period, which is unusually high. By comparison, the National Building Code of Canada [6] only requires a 30 year return period for strength design and 10 year period for serviceability design. The AIJ provisions give a formula for conversion between return periods as shown in Table 16.

Table 16: Wind Load- Return Period Conversion

Return Period	Reduction Factor	Wind Force
100 years	1.0	91 kN
50 years	0.93	85 kN
30 years	0.89	81 kN
10 years	0.77	70 kN

With this information, it was possible to estimate the displacement of the isolation plane under design wind loads. Based on a total building weight of 650 kN (66 t), and total stiffness of four shear springs of 312 kN/m, it was found that the equilibrium under wind load would be reached at the displacements given in Table 17. These values illustrate the influence of the coefficient of friction on the displacement under wind load.

The calculated displacements are less than the design displacement of 500 mm for seismic load, nevertheless, they are significant for the longer return periods. It would be an issue of serviceability to determine the acceptable range of displacements under the various wind load levels.

Table 17: Wind Load System Displacement

Return Period	8% Friction (52 kN)	12% Friction (78 kN)
100 years	125 mm	42 mm
50 years	106 mm	22 mm
30 years	93 mm	10 mm
10 years	58 mm	0 mm

It is further critical that the isolator properties are verified by testing, and that they remain within an acceptable range during the life-time of the building.

6.7 Conclusions:

A passive seismic protection system has been proposed for the Canadian Home Concept. Various systems were considered and the most suitable was selected. The system consists of an isolation plane with friction sliders and rubber shear springs set on top of any type of foundation, as required by the local soil conditions. The system relies on the addition of concrete slabs immediately above the isolation plane to add weight to the structure in order to resist high wind loads without excessive movement. The house modules are assembled on top of the slabs.

This preliminary analytical study showed that the proposed solution would be effective in reducing the impact of a seismic shaking on the house. When compared with a fixed-base structure, the isolation significantly reduced floor accelerations and storey drifts. In the event of a severe earthquake, the safety of any occupants and the probability of the continued functionality of the house would be significantly increased.

Construction aspects of the solution are within normal techniques currently used for the construction of residential structures. The friction sliders and rubber shear springs incorporated in the design are either readily available or can be manufactured using standard production processes.

While a cost premium would be associated with the addition of the proposed protection system to a house, one of the objectives of the second phase work would be to optimize the design to minimize this added cost.

A relatively straightforward experimental and analytical program of research could provide sufficient engineering information to establish the viability of this system for the protection of small wood frame buildings. Recommendations for such a study are outlined in the last section of this report.

CHAPTER 7:
ARCHITECTURAL CONSIDERATIONS

7.1 Introduction :

In addition to purely structural matters, the work also considered some non-structural building aspects: services; building attachments such as : porches, steps, and carports; exterior finishes at grade; maintenance and post-quake remediation. The work also looked briefly at how the proposed approach would work in combination with alternative structural systems such as 2x4 and panelized housing systems.

These various elements were considered within the context that under the most severe anticipated quake conditions that, as noted in the structural section, the home would not move more than 500 mm off-centre. Further, it was taken that the services must be designed in such a manner that the home will remain functional in a post quake environment; although some relatively modest cosmetic repairs may be required.

7.2 Services :

Services constitute some of both the easiest and the most complex non-structural issues which must be addressed. This work covers water, sewer and gas services plus electrical and telecommunications lines as they enter the home, but does not involve meters and in-home shut-off connections.

To simplify inspections, maintenance and any post-quake repairs, it is suggested that all services enter or exit the home at a relatively common point. This point will inevitably be determined by the location of the sewer line whose position in turn is dictated by required drainage slopes on any horizontal runs under the home. However, wherever possible, the grade access point and accompanying floor access point should be somewhat out of either the main traffic areas, or primary living areas in order to accommodate the necessary access hatch. One exception occurs where the hatch can be 'hidden' under a tatami mat in a Japanese styled room. Such an approach is illustrated in Figure # 16.

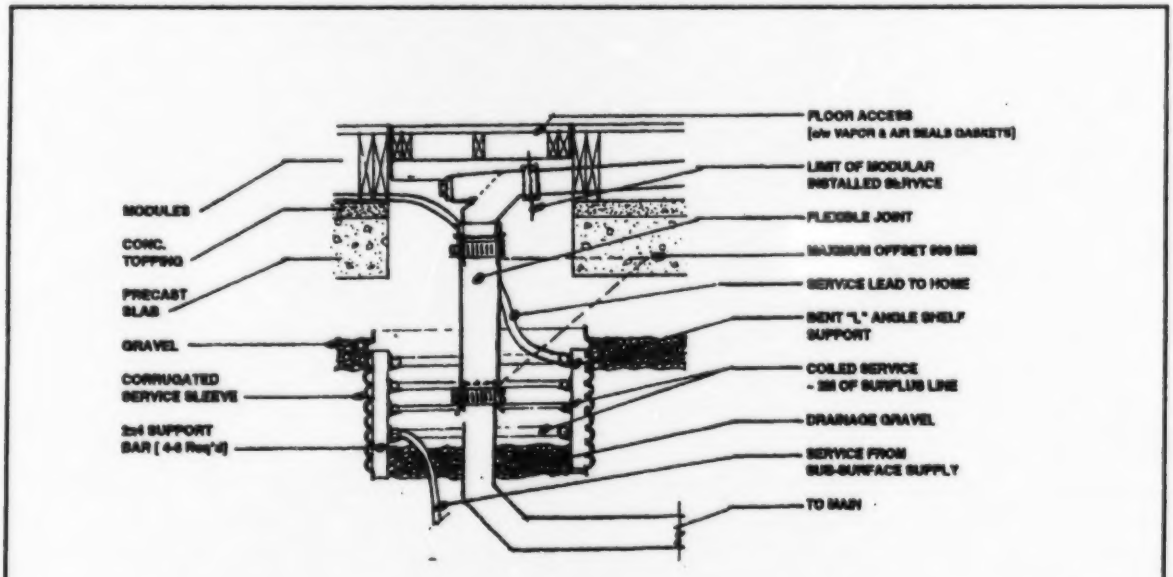

Figure 16 Section at Home Service Trench

For the RORO home used in this study, it is suggested that an appropriate service access location is in the hallway at the foot of the stairs. While a more convenient location might be assumed to be in front of the bathroom sink, a hatch at this location could cause problems in creating a waterproof flooring system in the bathroom/furo area.

Below the access hatch there will be a corresponding hole in the pre-cast concrete slab which is in turn positioned over the at-grade service pit.

The service pit can be constructed to any level of finish desired by the contractor, or dictated by the marketplace; however, this study proposes using a two piece corrugated metal sleeve some 500 mm in height which creates the clear space necessary to accommodate 500 mm +/- earthquake induced displacement in building services. As discussed below, it is assumed that only the semi-rigid waste stack will require off-set protection. Whereas the sleeve only extends some 360 mm above the waste stack's exit point from the ground, a 500 mm off-set at the top of the stack will only require a 300 mm off-set at the lip of the sleeve. Consequently, the total minimum diameter of the sleeve need not be much more than 700 mm, even allowing for the side mounted service racks discussed below; although, a wider sleeve might make any post-quake remedial work easier. Further, it should be noted that in cold climates some form of insulation or water service line electrical heat tape will have to be included and accounted for in the sleeve dimensioning.

Sewer Lines:

The sewer line constitutes both the most difficult, and in some opinions, the least important service connection to be protected.

It is unimportant because it doesn't explode like gas, it doesn't create deadly shocks like electricity, and unlike the water supply, alternate , albeit messy, alternatives can be fairly easily devised when formal city services are cut off. Furthermore, it is the one service which is user controlled and flows outwards as opposed to the semi-automatic incoming water service. An uncontrolled charged water line breaking down-stream of the house shut-off valve can cause extensive, foundation washouts, but one can *elect* not to use their toilet.

Finally, a broken sewer line is perhaps the easiest service line to repair. With simple tools, a couple of extra fittings and a spare length of line, even an average skilled homeowner could replace the house-line connection piece. Regardless of any innovative solutions offered below, a contractor may wish to leave sufficient spare materials in the service trench to allow for just such a post-quake repair as an insurance policy and choose to market same as part of their 'quake-proofing' package and sales pitch.

The sewer connection is described as difficult because unlike the other more 'flexible' services discussed below, a waste stack must be relatively rugged, rigid, straight and of a smooth bore. This tends to eliminate such options as loops, or some of the expandable accordion pipe options available on the market today for various uses.

With these requirements in mind, the simplest solution is to insert into the line an expandable, reinforced, rubberized section of hose to accommodate any home displacement. This will cost from $35.00 - $50.00 per home.

Where such a line substitution is not permitted, a more complex solution might involve the following design approach. If we assume a 100 mm main waste stack from the home, that line is fed into a flexible 110+/- mm line or hose which is clamped only at the upper end to the house waste stack. This 110 mm line is then in turn feeds loosely into a lower 150+/- mm rigid sewer line. By allowing the 110 mm line or hose to extend approximately 400+/- mm into the 150 mm pipe we provide sufficient excess line such that in a quake, the 110 mm line, which is loose at the bottom end, is able to lift or extend and move sideways under a quake offsetting force. For economy, the 150 mm line can be subsequently reduced back to the 100 mm dimension which is more typical of a residential sewer line connection.

To provide for system closure, the entire connection assembly is covered above and below the various clamp joints by an expandable accordion neoprene or plastic boot, such as the 'Gortiflex Convoluted Tubing' which contains any odours and excludes vermin. The total cost for such a system would be in the range of $200.

Though more complex than the first system which relies on a proprietary tubing, the second approach is comprised of readily available off-the-shelf components and can be jury rigged in an emergency whereas the more technically sophisticated expandable line may not be obtainable in a post-quake environment except where a spare has been left in the service trench by the contractor.

Power & Telecommunications:

Wire based services can be readily accommodated by providing additional lengths of line in the service trench. While the various power and communication links must be separated to prevent static interference, this should not present a problem.

To assist in organizing the wires, and other 'flexible services, one can attach four to eight pressure treated 2x2's around the perimeter of the corrugated service sleeve. To these in turn are attached simple angle brackets upon which the various services are set or hung. By providing the angles with a very slight upward bend, they will normally hold the service lines in place in a static situation, but readily allow them to slip off the supports to accommodate movements during a quake. Based on a service sleeve diameter of some 700 mm, this will provide approximately 2000 mm of excess service line length, more than sufficient to meet any needs.

While this work has assumed that all services will be buried, some installations may have to accommodate overhead telecommunication and power lines. In those instances, one need merely to allow an extra 500-600 mm of carrier cable and service lines between the adjacent telephone pole and the home. This approach produces a slight additional drop in the line, but allows sufficient slack to accommodate the home's maximum anticipated movement of up to 500 mm.

Water-Gas & Kerosene Lines or Pipes:

These three services are grouped as they tend to be delivered to the residence in some form of rigid pipe and thus require a common solution. That solution is some form of flexible piping or tubing which like the wired based services can be coiled loosely around the inside of the service sleeve.

To this end, a wide variety of flexible water piping is currently in use and doesn't require discussion. However, flexible gas piping while available is somewhat less common and thus is addressed. One product which a contractor can consider is a flexible gas line made of corrugated stainless steel tubing inside a heavy duty PVC sleeve. Marketed in North America under the trade name "WardFlex", this tubing was originally developed by Hitachi in Japan where it is marketed as "Soflex".

Whereas the 'Soflex' tubing has a minimum bending radius of only 75mm (3"), even in its thickest 25mm (1") diameter size, this product can be readily introduced inside the 700 mm service sleeve.

Smaller diameter tubing, in the 8 mm-10 mm range is used to connect individual outside kerosene storage tanks to many homes. While they could be replaced with flexible high-tech lines, even when done in copper, these lines can also be fitted within the service trench and corrugated service sleeve.

Like the electrical services, these 'piped' options can be supported on angle brackets mounted on the 2x4's around the service trench sleeve.

In summary, it would appear that earthquake-resistant services, or service connections can be readily and economically introduced in support of the seismic-resistant foundation system.

7.3 Attached Structures:

The work also looked at how steps, porches and carports might be designed in order to minimize their potential quake damage. These structures can have a lower survivability expectations as they are not

critical even if damaged beyond the 'functional' continuity being demanded of the home itself. Full garages were excluded as they are considered to be similar to the home itself and thus would require the same level of 'functional' quake protection on seismic resistant foundations.

Porches & Steps

Porches and steps constitute the first level of attachment and require two modest interventions to ensure their protection. First, the deck or step must be very firmly attached to the basic house structure. Any headers, bearing ledgers or joists must also be either bolted or strapped to the home to provide a positive connection under any tensile forces during the quake induced move. At the outside edge of the porch or steps the bearing member, either a short post or stair stringer should terminate in a smooth, sliding surface such as a rounded end cap which has been fitted with a heavy duty galvanized metal sheet. This end should in turn bear on a smooth structural support such as a trowelled concrete pier cap, pile or slab-on-grade pad. The actual support will be a function of soil and frost conditions. However, as the home is designed to slide up to 500 mm any *any* direction, the bearing surface must be sufficiently large to accommodate this movement without breaking or toppling the bearing post. For safety, a minimum pad of some 1,300 mm square is recommended. A schematic sketch of such a post and pad is illustrated in Figure 17

Minor Porch & Entry Roofs

These structures can be designed in such a way to be fully supported as cantilevered structures hanging from the home itself. These attachments will need to be properly designed to rely on a combination of bracing brackets and strap attachments and as such, overhangs of up to 1,200 mm should be possible with a minimum of difficulty or cost.

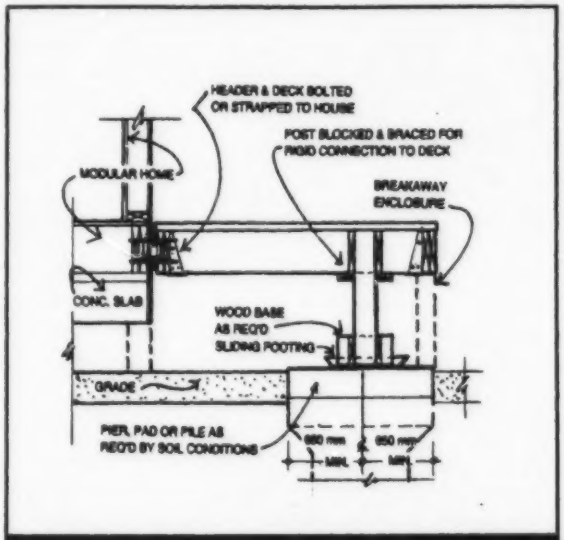
HEADER & DECK BOLTED OR STRAPPED TO HOUSE
POST BLOCKED & BRACED FOR RIGID CONNECTION TO DECK
MODULAR HOME
BREAKAWAY ENCLOSURE
CONC. SLAB
WOOD BASE AS REQ'D SLIDING FOOTING
GRADE
PIER, PAD OR PILE AS REQ'D BY SOIL CONDITIONS
MIN.
MIN.

Figure 17 : Typical Post & Stair Bearing Detail

Carports and Major Porch Roofs

This class of structures are difficult to protect during an earthquake. Often designed for maximum views, or minimal weather protection, these attachments are sometimes little more than roofs attached to a home on one side and two corner posts on the other.

In a single family residential setting, carports generally lack the required bracing and tend to collapse onto the car. However, there is the additional problem that such a collapsed structure **could** impede the movement of home on its seismic sliders and springs and thus negate any potential benefit the proposed system might provide.

Obviously, these major attached structures can be built to any required, or desired, standard; however, this could result in such a significant cost penalty that nothing is done. The following suggestions attempt to bridge that gap between total support and none, and do so in a cost effective manner. Against this background, it is suggested that any of these larger roofed attachments be constructed in an "L" shaped configuration as shown in the following Figure 18.

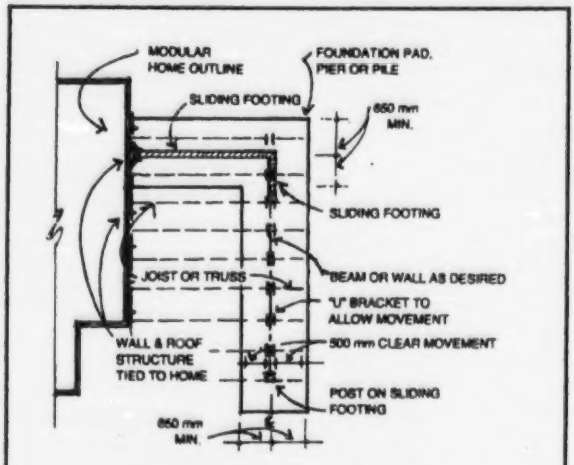

Figure 18:Carport Foundation / Roof Plan

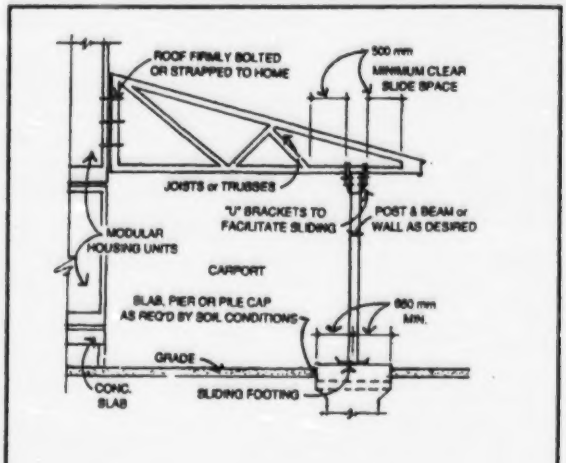
ROOF FIRMLY BOLTED OR STRAPPED TO HOME
500 mm MINIMUM CLEAR SLIDE SPACE
JOISTS or TRUSSES
"U" BRACKETS TO FACILITATE SLIDING
POST & BEAM or WALL AS DESIRED
MODULAR HOUSING UNITS
CARPORT
SLAB, PIER OR PILE CAP AS REQ'D BY SOIL CONDITIONS
650 mm MIN.
GRADE
CONC. SLAB
SLIDING FOOTING

Figure 19 Carport Section

Both the end and the side elements should be fairly rigid and where possible firmly attached to the home. As with the smaller attachments, the outside bearing should be designed to slide and thus set on pads with at least 600 mm of clearance all round.

In addition, it would be helpful if the roof structure could be configured in such a manner that it is free to slide up to 500 mm -600 mm and to that end, it is necessary to have the lower cord of any trusses or tie rafters sized and built to have a 600 mm extension to the outside of the long supporting side. Then, if as shown in Fig. 19 the main residence shifts 500 mm to the left, and the supporting wall or column stays more stationary, the lower cords will slide left, but still provide adequate bearing for the roof structure. Obviously, this detail must prevent uplift during strong winds, but the overall detail is neither complex nor expensive.

The advantages of this slippage detail is that in roughly one half of the quakes it should prevent collapse of the looser roof or damage to an expensive vehicle and further allows for its removal and possible escape from the area if necessary.

While discussed below under landscaping, it bears noting that the base planes of any major carport or large deck, must be located below any part of the residential structure such as the modules, pre-cast concrete slabs, or extension position of sliders and springs in order to permit their free movement in a quake situation.

7.4 Landscaping & Grade Finish :

One needs to consider two matters at grade: the hard and soft landscaping plus the closure of the gap between the pre-cast slabs and the grade itself.

Landscaping:

The first of these is relatively easy to address by simply noting that nothing at grade, within 600 mm of the home, such as major decks, patios, airconditioner or equipment pads, posts walkways or driveways should be allowed to rise closer than to within 100 mm of the underside of the pre-cast concrete slabs. This will allow a sufficient safety margin for the free movement or displacement of the entire home under quake conditions.

In a somewhat similar vein, major landscaping elements, such as rocks must be placed with care. Even bushes, which when new may not be able to

withstand the force of a 69,000 kg home moving 500 mm under a .5g load, however do tend to grow thicker, larger and stronger. Consequently, over time, a decorative planting could mature and possibly impede the free movement of the home and reduce the effective operation of the seismic sliders. While one can't write comprehensive rules in this area, it might be wise to suggest only a flower bed, gravel or low ground cover for the first 500 mm out from the base of the home.

System Closure

The sub-module closure system serves two purposes: first to exclude water and vermin, and secondly to provide a suitable exterior finish. However, any proposed solution must meet three technical requirements: (a) allow free movement of the home during a quake, (b) accommodate any modest independent ground or home movement and settling over time and (c) allow for removal and inspection or maintenance of sliders and springs.

These goals and criteria can be met by introducing a simple slip-joint type of panel closure as noted in Figure 20 (a) and (b). This approach encompasses a number of elements. Sloped drainage away from the home will minimize most moisture. However, care should also be taken to ensure that roof rain water leaders (down spouts) either drain away from the home as surface water, or to rock pits and municipal services as prescribed by the prevailing local codes. Similarly, the ground layer under the home should incorporate a damp-proof membrane and be properly drained. The gravel layer shown on the various cross sections is essentially a cosmetic element and can be eliminated or replaced with sand provided that drainage is maintained. The pressure treated edging provides both a convenient stop between materials and acts as a fastening base for the lower components of the closure system. The closure system itself is essentially just two overlapping panels acting either as a base trim or incorporating site applied siding to match the home. The key feature of the system is the

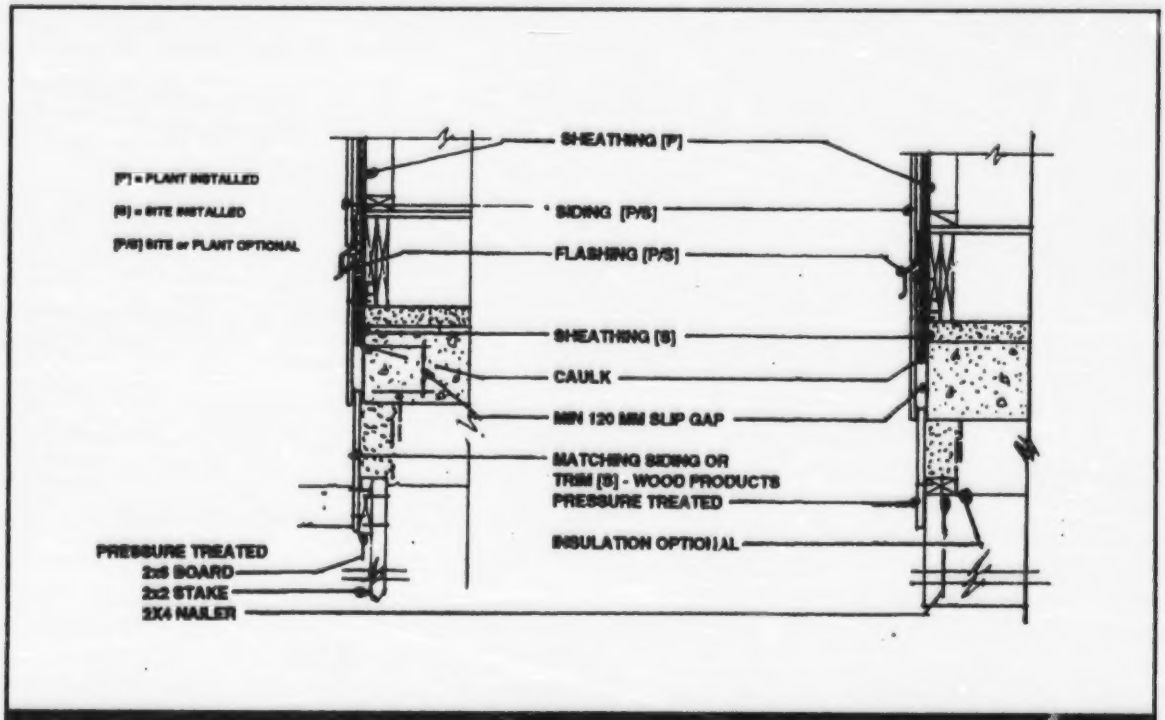

Figure 20: (a) Closure Section Between Piers (b) Closure Section at Piers

manner in which the two panels can slide past each other by 100 mm to 150 mm to accommodate any movement in the ground plane versus the home. Generally, this movement occurs when a home is placed on a secure foundation which has its own bearing below either the frost line or a surface layer of expanding clay. In those instances, the home foundation and hence the home remain fixed while the grade below fluctuates with the seasons.

In North America this is similar to many foundations found under mobile homes. When in colder climates the underside of the home is enclosed with a sturdy, and often insulated 2x4 pony wall bridging between the home and the grade, it is not unusual to have instances where the homes are actually lifted up off of their foundations due to soil expansion acting up through the closure wall.

While this system must be sufficiently sturdy to withstand normal wear and tear or strong winds, it must also be capable of breaking away during a quake episode. In this regard, the damage or loss of the closure system is considered acceptable and is not part of the 'functional continuity' which has underlain the overall house foundation approach.

Finally, the proposed detail allows for the easy removal of the panels for inspections of the seismic foundation system or the sub-residence space. While the overall clearance of 200 mm under the home does not facilitate physical access this is not deemed problematic as both the services and the seismic piers can still be readily viewed. In addition, the 500 mm clear space around the springs allows for access and their replacement or servicing albeit in a somewhat cramped space and only after there has been very modest excavation at those points and removal of the pressure treated retaining walls, but as such action may never occur and if it does, it will only be at very extended periods, 10 years +/- , this is not considered to be an issue.

7.5: Post Quake Remediation

It is accepted that even with the extensive seismic mitigation systems being proposed that there could be a residual building offset following a significant quake. In those instances where the offset is deemed unacceptable from either an aesthetic; legal, unit too close to the property line; or structural perspective, it would be possible to realign the home by either pulling or pushing on the concrete slab units which underlie the home modules. Because these slabs have been joined either through the bolted friction plates or by spot welds on inset plates along their seams it should be a minor matter to shift the entire concrete 'platform' the anticipated modest amounts. This realigning force can be achieved either with a heavy vehicle or by acting against an adequately braced nearby fixed point.

7.6 : Alternative Structural Systems

While the primary objective of this work was to devise an earthquake resistant foundation system for use with modular units, it was recognized that any solution might have application with either a modified version of post and beam, new 2x4 or panelized Canadian export housing products. To this end, these various construction systems were evaluated in terms of use with the final proposed approach.

The resulting foundation solution, with its required use of the intermediate concrete slabs, is essentially an elevated 'slab on grade' resting on a seismic float system. Consequently, like a slab on grade, the overall system, with the appropriate reinforcement, can accommodate any of the standard construction systems currently in use be they posts or panels. To this end, all Canadian exporters, whether working with modified post and beam, pre-cut or panelized structures can modify and utilize this foundation approach as part of their own Canada Home Concept product.

CHAPTER 8:
APARTMENT APPLICATION

8.1: Introduction

While Earthquake Resistive Foundations [ERF] appear to have merit in the single family housing market as part of a broader Canadian Home Concept, they may have even greater potential in the multi-family construction environment where they can protect more units and more people in a concentrated and cost-effective manner.

Further, such an application would support the continuing efforts by the Canadian government and the Canadian export housing industry to promote the use of wood framing in the multi-family, and multi-storeyed residential market. This direction is evidenced by their support for, and success in effecting changes to the Building Standard Law of Japan to allow a much wider use of wood in these types of structures.

8.2: System Design

This Section takes a *general* look at the design and application of an ERF approach as applied to a typical 3 storey, wood-framed, multi-family apartment building.. This is not intended to be an engineering analysis to the same degree as the work in the previous Chapters on the single family residence. Rather, it is intended to *suggest* to the typical reader how the forces acting on an apartment will vary from those acting on a single family residence, what differences exist and how any new building or system requirements can be met.

It is assumed for this brief analysis that the internal structure and rigidity of the double-building width, multi-module apartment has been so modified as to allow it to respond in a unified manner similar to the smaller and conceptually simpler house.

Finally, the reader will recall that in Section 5.6, it was noted that a 200 mm thick pre-cast concrete slabs were added to the home to provide additional weight, and hence frictional resistance through the sliders to counteract prevailing design wind loads. In the apartment design, these slabs have been eliminated based on the expectation that the added weight of the extra floor and the increased building cross-section will off-set that weight reduction.

8.3: Analysis

Assumptions

To simplify the analysis of an ERF supported apartment building, one needs to recall that in the case of the single family residence the wind load was 0.3g as opposed to the 0.2g load which was mandated for earthquake resistance. It is possible to compare an apartment and a family home by comparing the foundation designs necessary to counter the design wind loads.

To simplify the comparison, we have assumed that the same seismic sliders are utilized to support both buildings; although, the reader can appreciate that in the finely engineered situation which would typically be applied to a multi-family structure that it would be reasonable to expect that the apartment building would be supported by a more efficient and hence overall less expensive structural system.

Further, it is recognized that while the RORO home which was used as the basis for the earlier analysis is essentially a square structure, the configuration of most apartment buildings tend to be a longish, double loaded corridor structure. Therefore, in order to facilitate a simple comparison, the analysis shown in Figure # 21, on the following page considers only a three bay segment of the apartment building thus being somewhat similar to the three bay residence.

Application

In brief, one can state that the selected sliders under both buildings have an inherent resistive coefficient of friction (f) which under the building design load, or weight, (W) generates a total resistive force which is equal to the maximum design wind force (F) or,
(W) x (f) = (F)

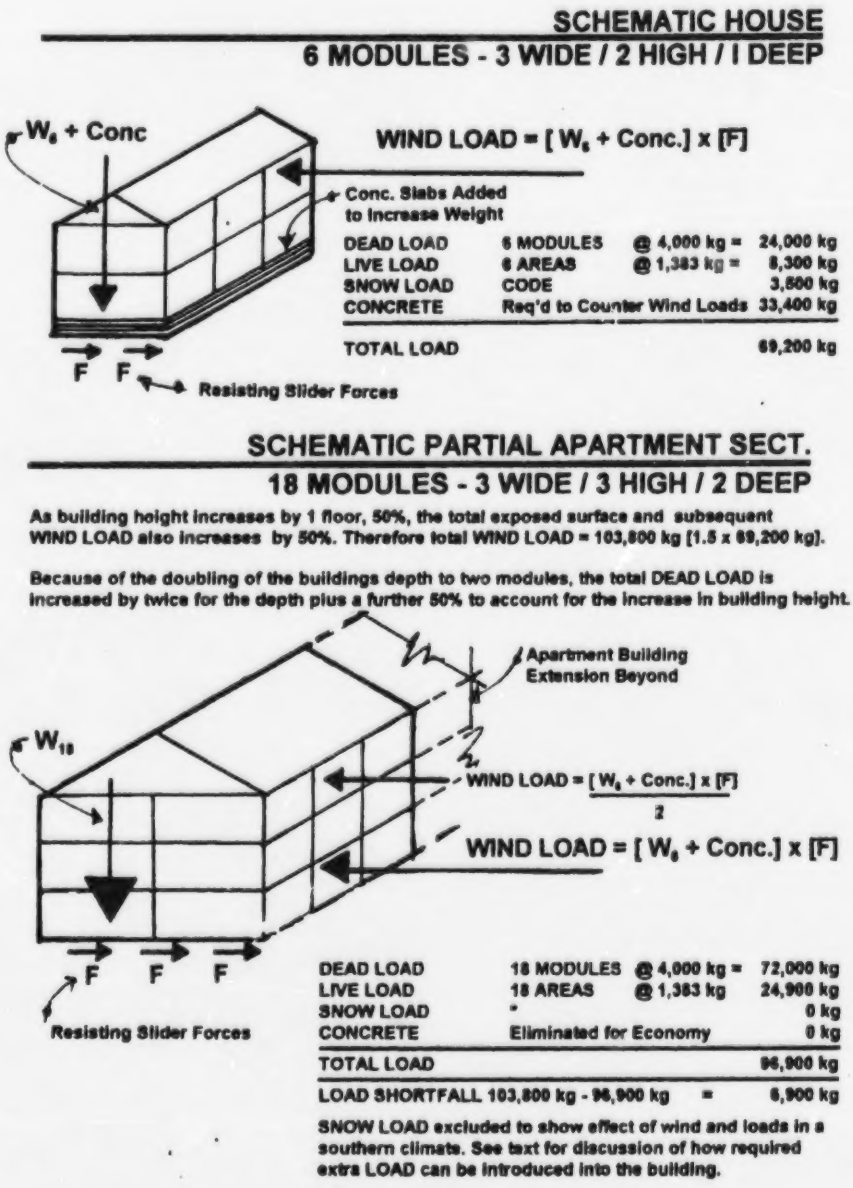
SCHEMATIC HOUSE
6 MODULES - 3 WIDE / 2 HIGH / 1 DEEP
W6 + Conc
WIND LOAD = [W6 + Conc.] x [F]
Conc. Slabs Added to Increase Weight
DEAD LOAD 6 MODULES @ 4,000 kg = 24,000 kg
LIVE LOAD 6 AREAS @ 1,383 kg = 8,300 kg
SNOW LOAD CODE 3,800 kg
CONCRETE Req'd to Counter Wind Loads 33,400 kg
TOTAL LOAD 69,200 kg
F F
Resisting Slider Forces
SCHEMATIC PARTIAL APARTMENT SECT.
18 MODULES - 3 WIDE / 3 HIGH / 2 DEEP
As building height increases by 1 floor, 50%, the total exposed surface and subsequent WIND LOAD also increases by 50%. Therefore total WIND LOAD = 103,800 kg [1.5 x 69,200 kg].
Because of the doubling of the buildings depth to two modules, the total DEAD LOAD is increased by twice for the depth plus a further 50% to account for the increase in building height.
Apartment Building Extension Beyond
W18
WIND LOAD = [W6 + Conc.] x [F] / 2
WIND LOAD = [W6 + Conc.] x [F]
F F F
Resisting Slider Forces
DEAD LOAD 18 MODULES @ 4,000 kg = 72,000 kg
LIVE LOAD 18 AREAS @ 1,383 kg 24,900 kg
SNOW LOAD * 0 kg
CONCRETE Eliminated for Economy 0 kg
TOTAL LOAD 96,900 kg
LOAD SHORTFALL 103,800 kg - 96,900 kg = 6,900 kg
SNOW LOAD excluded to show effect of wind and loads in a southern climate. See text for discussion of how required extra LOAD can be introduced into the building.

Figure 21 : Analysis of Wind Loads on Prototypical Apartment Structure - Representative Section

However, as (L) and (F) are related by a constant, which is the coefficient of friction, one can essentially ignore that factor (f) and state that the required resistive force, or building weight, and the wind bear a direct relationship. That is to say, "if the wind force doubles, then the building weight must also double in order to counteract it. Due to the relatively simple context in which the house and the apartment are being compared, and in recognition of the building industry's greater familiarity with the

weight of building materials rather than complex engineering concepts this approach is used in the comparison and analysis illustrated in Figure 21.

As noted above, the apartment structure, without the concrete slabs is some 6,900 kg (15,200lbs.) short of the total building weight required to properly counteract the prescribed wind design loads.

NOTE:

The snow load has been eliminated from consideration in the apartment analysis in order to create an example which has application throughout Japan.

The required weight shortfall noted above , some 6,900 kg or a little over 3t. is almost inconsequential compared to the many unknowns which exist in even the most generalized discussion being presented in this section. However, in order to afford the reader a better appreciation of the nature and scale of that shortfall, the following text considers how one might readily compensate for such a shortfall through normal construction practices. As such, the following section should be read as general information rather than a detailed construction recommendation.

Within the context of the construction industry the 6,900 kg represents a very modest shortfall even when considered over the limited scale of the *slice of the structure* represented by just the three double depth structural bays. Adding the required weight can be readily achieved in a number of ways through modest changes in material selections or general construction practices. These means include the following representative examples.

Roof :

- Assuming a flat roof, we have a working area of some 145 m^2.
- Therefore we need to add 6,900 kg/145 m^2 or 47.6 kg/m^2 (4.4#/sq.ft.)

On a flat roof this can be easily achieved by using either a 25 mm gravel topping on a built-up roofing system or using 25 mm concrete pavers, possibly on an inverted roof membrane.

Floors :

- Three floors at 145 m^2 equals a working area of some 435 m^2
- Therefore we need to add 6,900 kg/435 m^2 or 16 kg/m^2 (1.5# /sq.ft.)

This required additional burden can be achieved by replacing light-weight carpets with either hardwood flooring at 20 kg/ m^2 (4# /sq.ft) or ½" quarry tile at 26 kg/ m^2 (5.8#/ sq.ft.).

Alternatively, if one wishes to simultaneously improve both the construction quality , fireproofing and acoustic attenuation, they could add a light-

weight concrete floor topping. Whereas the acceptable minimum topping thickness is in the order of 18 mm or 3/4", this constitutes an additional load of 38 kg/ m^2 or 7# sq.ft.

Exterior Walls :

- The total area of both faces of the three storeys of the three bays under consideration equals 152 m^2
- Therefore we need to add 6,900 kg/152 m^2 or 45 kg/m^2 (4.2# /sq.ft.).

This load can be achieved either through the use of a conventional 18 mm (3/4") stucco or 10 mm (3/8") exterior tile.

Regardless of the approach adopted it is evident that the required additional load necessary to make the seismic sliders function effectively can be readily introduced into the apartment building design through a number of ordinary , cost-effective and non-intrusive material selections.

8.4 Summary

Based on the above analysis one can conclude that a SRF system can be effectively and efficiently introduced to protect multi-family wood-framed apartment buildings. Most importantly, the concrete slabs which are necessary, but non-structural, components of the single family house approach can be omitted in the apartment building and any shortfall in weight compensated for through normal material selections that have essentially no subsequent impact on the apartment building's construction budget.

It would therefore appear that Seismic Resistive Foundations might enjoy greater market acceptance and market penetration in the multi-family sphere of residential construction and consequently could reasonably form one focus and selling point for Canadian Home Concept exports.

The importance of this potential market is best understood when one considers that in the late 90's, the annual mature market for 2x4 homes ranged from 250,000 to 350,000 units or an average of 300,000 single family 2x4 homes. Of these Canadian panelized *and* modular exporters expected, at best, to secure some 8,000 to 12,000 units. During that same period, the number of apartments built annually was in the order of some 775,000+/- and of these some 135,000 units were of wood construction and save for a demonstration building, Canadian exporters secured essentially none of that market .

It quickly becomes obvious that even if a modest share, say, 20%, of the traditional wood framed buildings and a smaller, 5% of the non-timber buildings were modularized, the resulting market of some 59,000 units would represent a particularly attractive target market for Canadian exporters and potentially far surpassing our expectations from single family home sales. It is against this potential market that the idea of modularized apartments, and particularly apartments with an integral seismic resistive foundation system must be viewed.

CHAPTER 9: COMPARATIVE COST ANALYSIS

9.1 Introduction & Approach

Obviously, engineering prowess is only one measure of a technology's success. Cost effectiveness, or perceived cost-benefit must also be considered when rating that technology's overall market potential .

To this end, a comparative cost analysis of a traditional foundation system and the proposed earthquake resistant foundation was undertaken to provide a *general* insight as to any potential cost increases or savings which will confront a builder wishing to offer such a housing option or a consumer contemplating an improved structural package. The resulting cost increase was then considered within the context of the prevailing Japanese housing and financing market to gauge the potential consumer acceptance of ERF systems..

Finally, a preliminary analysis was made as to how these costs might apply to the prototypical three storey, wood framed apartment building discussed in the last Chapter.

Comparative costs were sought only for those foundation elements which differed between the two systems. Given what one might call the 'commonality of support' which one finds between the standard foundation walls and the proposed pre-cast slabs it was assumed that the design, fabrication, shipment and placement of the modular housing components would be essentially identical in both foundation systems.

Further, as discussed earlier, given a general overview of typical 2x4 , post and beam and panelized systems, it would not be inconsistent to suggest that the seismic resistive system could accommodate all typical housing systems and thus the comparative foundation analysis will be generally valid regardless of the construction approach being adopted at the single family residence level.

Finally, it is assumed that these two *particular* foundations being compared are located in an area where the followings conditions prevail:

- frost penetration is less than 730 mm -or- sufficient ground insulation can be introduced to effect an "Insulated Shallow Footing" and
- soil conditions have sufficient compressive strength, resistance to liquefaction and non-expansive clays such that the foundations can be of conventional design.

The reader can appreciate that when dealing with a nation where soil conditions run from tropical clays in southern Kyushu to temperate fills over previously low-lying farming areas around the earthquake prone central Osaka Bay or even the cold climate soils of northern Hokkaido there exists an almost unlimited number of combinations of foundation conditions which must be addressed. However, it is assumed that where unique foundation under-pinnings are required, such as deep piles, that they will also be common to both of the systems being priced, and that the general comparative analysis will remain valid.

Naturally, should one contemplate the use of a seismic resistive foundation approach in any specific real-life situation, it will be incumbent upon the designer or contractor to engage appropriate professional services to investigate and confirm the necessary final design requirements.

However, this costing analysis assumes a stable temperate site which allows one to concentrate on the specifics of the *primary* seismic foundation elements themselves. Consequently , the following two cost analyses only consider that zone of the structure from the underside of the wooden modular units to the bottom of the gravel fill under any footings or pads.

Against this background, costs were secured from three mid-sized Japanese residential contractors in the Tokyo area each of whom produces 60-80 single family homes a year. In order to simplify the costing exercise, each contractor was provided with the base drawings which are contained throughout this report plus a materials take-off. Concurrently, costs were secured from a similarly sized Canadian contractor working in the Kelowna ,B.C. area and these costs were used to identify any significant variations in Japanese costing either between the two systems or between the elements within the seismic resistive system itself.

9.2 Costs

The above exercise for the two different systems generated the following comparative costs:

Standard Foundation	$16,900
Seismic Foundation	$19,800
Seismic Sliders & Springs	$15,000
Total Seismic Costs	$34,800
Cost Differential	**$17,900**

A detailed costing sheet can be found in Table 18 on the next page

9.3 Cost Analysis & Impacts

Not unexpectedly, the combined piers and precast slabs required to make the seismic foundation components operative cost more than the traditional crawl space foundation for a similar sized home. In this instance 17 % more or $19,800 versus $16,900. However, what is particularly interesting is the finding that 65% of that cost is attributed solely to the concrete slabs. In essence, the actual functional foundation , as it applies strictly to the excavation, piers, footings and gravel costs only one-third that of the traditional foundation. As will be seen, this has a particularly important impact in an apartment scenario.

While a seismic resistive foundation is more costly than a conventional foundation, the homeowner does enjoy a considerable increase in life safety during an earthquake. Furthermore , and of increasing perceived consumer importance, homes on a seismic resistive foundation will suffer less "functional" damage; that is to say, that in addition to providing a safety benefits such as non-collapse, these homes will be subjected to a minimum of wall cracking, loss of level, racking out of square and furniture overturn or cupboards being emptied and their contents damaged.

In essence, these homes remain fully functional. This functional protection is being increasingly seen as not only a desirable trait, but rather as a mandatory constituent for a contemporary residence and hence as an added benefit or value for which the homeowner will pay. The question remains as to how much of a premium they will pay for this benefit.

While the scope of this project did not encompass a market analysis, it should be noted that while the cost increase of the seismic resistive foundation over a conventional foundation is $17,900, for homes in the Tokyo area which run an average of $610,000+/- this constitutes a 3 % increase . In national terms, these foundations would represent a 3.5 % increase on the average national home cost of $533,000 +/- .

Mortgage Costs:

To put this into more immediate terms, at this writing, Japanese residential mortgages rates are in the range of 2.6%. That means that with an amortization period of 30 years, the increase in monthly mortgage payments to accommodate the improved foundation system will run approximately $71.00. Whereas many new Japanese homes are bought with up to a 50% down payment, the $71 represents a 6.7% increase in the typical monthly mortgage payments of some $ 1,057. Anecdotal discussions with knowledgeable players within the Japanese construction industry appear to suggest that such an increase is quite reasonable and thus one which could foresee a market niche for this type of seismic resistive technology at the single family residential level

Table 18 Comparative Japanese Foundations Costs - Traditional vs Earthquake Resistant				
		Traditional Foundation	**Seismic Resistant Foundation**	**Reader's Notes / Comparative Costs**
Item	**Activity**	[Canadian Dollars]	[Canadian Dollars]	
	Excavation			
1	Excavation	2,939	1,437	
2	Dump Truck	266	260	
3	Gravel	431	431	
4	Labour	89	43	
5	**Excavation Sub-Total**	**3725**	**2,171**	
	Foundation			
6	Rebar	2,464	349	
7	Concrete	2,740	2,016	
8	Forms	1,127	646	
9	Labour Footing	3,156	1,448	
10	Labour Slab	3,687	724	
11	**Foundation Sub-Total**	**13,175**	**5,183**	
12	**TRADITIONAL FOUNDATION TOTAL**	**$ 16,900**	**Sub-Total 7,354**	
	Pre-cast Conc. Slabs			
13	Concrete		1,353	
14	Labour		4,343	
15	Crane		299	
16	Service Sleeve		646	
17	**Concrete Slab Total**		**6,641**	
	Concrete Topping			
18	Concrete		1,396	
19	Wire Mesh		1,185	
20	Labour		3,221	
21	**Concrete Topping Total**		**5,801**	
	SEISMIC FOUNDATION SYSTEM TOTAL		**$ 19,800**	
	COST DIFFERENTIAL		**$ 2,900***	

*Does NOT include Seismic Sliders or Springs

Insurance Costs:

One must also consider any potential savings a homeowner might enjoy as a result of potential savings in insurance costs. Typically Japanese earthquake insurance is only available as a rider on a standard residential fire insurance policy and even then, is only available for amounts ranging from 30% -50% of the value of the home, as defined by the amount of the fire insurance. Furthermore, there is a payment ceiling of 50¥ Million for a home and 10¥ Million for contents.

Understandably, the rates charged for quake insurance will vary both by the type of home construction and the risk factor, ranging from level one thru four , with four being the most dangerous, as defined by the location of the home. The effect of these conditions is that there is an almost limitless range of potential insurance costs.

However, if we just look at the insurance rate charged on a typical new 2x4 framed home in Japan, costing $533,000, located in the worst quake zone, the area most likely to benefit from and utilize ERF's we generate the following analysis:

House Cost	$533,000
Maximum Insurance Coverage 50%	$ 266,500
Contents	$ 100,000
Maximum Insurance Coverage 50%	$ 50,000
TOTAL INSURANCE COVERAGE	$ 316,500
Insurance Rate	0.175%
Insurance Cost	$ 554 / yr
Seismic Foundation- 30 Yr. Mort.	$ 852 / yr
Premium of ERF over Insurance	**$ 298/ yr**

But it must be remembered that the insurance coverage is only for 50% of the home. To provide the same 100% level of protection as afforded by the seismic foundation with insurance , *if it were available*, would actually cost $276.00 more per year than the Earthquake Resistant Foundations.

Against this background it would appear that Japanese consumers have an option of either purchasing expensive insurance which will only **compensate** them for **50% maximum** of their earthquake losses, or they can invest slightly more in dollars terms, but less on a percentage basis, to have their homes incorporate a foundation system which will **prevent** almost **100%** of any damage.

9.4 Apartment Costs:

As noted above, the seismic resistive foundation may find its most appropriate application within the three storey, wood framed, multi-family housing market. Consequently, costs were also briefly analyzed for this type of building. This analysis was based on the following broad assumptions:

- Typical new apartments run $50m^2$ to $58m^2$
- Construction bays-preferably modular are similar in scale to those used for the home and run the average 2.9m in width which is the maximum highway shipping dimension
- Buildings are three storeys and each organizing section has four apartments per floor for a total of twelve suites.
- The same springs and sliders will be as used as in the home. However, it must be understood that this merely reflects a simple evaluation. In reality, the seismic response for a a major multi-family structure would be custom designed and one would expect it to be more efficient and hence less costly than one based on a single family home product sizing.

Under these conditions, a block of twelve large apartments encompassing some five structural bays will require eighteen sliders and eight springs similar to those already discussed and priced. A set of twelve smaller apartments stretching over only four structural bays would have a correspondingly smaller foundation requirement of some fifteen sliders but only four springs.

But most importantly, as discussed previously, because of the double building depth and the added third storey, the apartment building does not require the introduction of the precast concrete slabs to add needed weight. Subsequently, roughly two-thirds of the house foundations costs have been eliminated from the apartment option and costing analysis.

Extrapolating from the cost of the home foundations, it is estimated that the 'foundation' components for a 4 bay building option would cost approximately $15,200 while a 5 bay structure would cost slightly more at $18,700.

To these two figures must be added the cost of the sliders and springs in each configuration. These are estimated at $26,000 and $32,500 for the 4 bay and 5 bay structures respectively thus generating total costs of **$41,000 for a 4 bay apartment** building and **$51,000 for a 5 bay apartment** building.

This finding becomes most interesting when these figures are compared to the costs of traditional apartment foundations. Again, extrapolating from the house foundation costs, this time using the traditional crawl space approach it is estimated that a traditional Japanese crawl space foundation for the 4 bay and 5 bay apartment blocks would cost $43,500 and $53,500 respectively.

That is to say, Earthquake Resistant Foundations EFR's for apartment buildings cost approximately 5% LESS than traditional earthquake-prone foundations.

However, the reader should note that the above costing analysis did **not** include any additional costs which might be necessitated for improved module connectors or to ensure the even distribution of the building load to the footings. When one weighs these costs against a more efficient ERF which one might logically expect to find in a multi-unit structure, it may not be unreasonable to expect that the overall cost for traditional and earthquake resistant foundations will be comparable. Excepting that the ERF provides a far higher level of earthquake protection to the structure, its contents, the residents and the continued utilization of that multi-unit residential building for the purpose for which it was intended.

Although only a preliminary finding, if proven to be valid over a typical range of structures, the implications constitute a significant marketing, life safety and societal benefit and as such merit further investigation.

CHAPTER 10: SUMMARY CONCLUSIONS

Based on the above, we can draw the following conclusions:

- It is not currently possible to create a low-cost slab based Earthquake Resistant Foundation [ERF] system.
- It is possible to utilize conventional earthquake mitigation devices to protect a single family modular home. However, it is necessary to add mass, in this case by way of a precast concrete slab, to make the seismic foundation function as required.
- An ERF costs approximately twice as much as a conventional foundation for a standard two storey modular home with a 73 sq. m. footprint.
- The added cost for an ERF represents only about a 3% to 3.5% increase in the construction cost of a typical new home in Japan.
- Despite the foundation cost increases, a ERF **costs less** than a comparable level of quake insurance and offers full protection versus merely compensation for lost home, furnishings and family keepsakes; not to mention the potential saving of home based businesses which are becoming increasingly important. Further, Japanese homeowners can only get insurance to a maximum of 50% of the cost of their home. Therefore, the 100% protection of the ERF appears to constitute a good consumer option.
- The ERF devised for the single family home can be utilized in an apartment building setting. Fortunately, the pre-cast concrete slab which is required in the single family home is **not** required under an apartment building.
- Earthquake Resistant Foundation systems for apartment buildings are approximately **5% LESS EXPENSIVE** than the traditional, yet more earthquake prone foundation systems typically used under these types of structures.

CHAPTER 11: PROPOSED FURTHER RESEARCH

One of the objectives of this project was to recommend a research plan for a potential second phase effort which would undertake a detailed analytical and experimental verification of the proposed system and provide a detailed design of the system and its components. The ultimate objective of the second phase of the project will be to provide sufficient engineering information to design, build, and install the system as well as to gain acceptance in the Japanese market.

11.1 Proposed Activities

Performance Criteria

Conduct a survey of Japanese seismicity as it relates to earthquake loads on buildings.

Review Japanese building codes and design guidelines. Focus on provisions for design of protective systems.

Review building codes from other parts of the world, notably the Building Codes the US and New Zealand, for provisions for the design of protective systems.

Establish a range of seismic motions and criteria. Several sets of multidirectional earthquake motions will be required.

Establish performance criteria for seismic design. Establish service and wind load performance criteria, including vibration control and wind load resistance.

Establish criteria for functional performance, including requirements for inspection, maintenance and repair of special protective devices.

Analytical Verification

Build a three dimensional nonlinear finite element model of the structure. The model will include a realistic model of the modules and their properties.

Subject the model to earthquake motions established.

Verify that the performance criteria are met or exceeded by the analytical model.

Investigate the effectiveness of simplified code analytical procedure for practical analysis and design of the proposed system.

Experimental Verification

Design a scaled model of the system to be tested on the shake table at the UBC Earthquake Engineering Research Facility.

Prepare earthquake records for the use with the shaking table.

Perform analytical prediction of the performance of the experimental setup using the processed records. Secure the supply of test specimens of special devices from suppliers.

Perform a series of component tests on the individual special devices to verify their predicted performance parameters, including vertical and horizontal stiffness, and coefficient of static and dynamic friction. This work would take place at the Structures Laboratory of the UBC Civil Engineering Department.

Analytically re-evaluate the expected performance of the proposed scaled model based on the results of component tests of individual devices. Revise the design if necessary.

Construct the scaled model.

Perform a series of static tests on the model to verify the behaviour under wind and service loads. This item can be accomplished following the erection of the model on the shaking table.

Perform a series of dynamic tests, by subjecting the model to multi-directional earthquake motions.

Detailed Design

Based on the experimental and analytical results, prepare a design of the system components.

Perform a design of the superstructure with a particular attention paid to connections between modules.

Correlate a simplified design procedure with the analysis and the experimental findings.

Prepare detailed drawings of the system, including layout, sections, connection details, details of components, etc.

Outline the key issues involved in the design of future additions to the buildings and appendages such as stairs, patios and porches.

Examine the range of applicability of the design under various combination of design parameters.

Prepare foundation designs corresponding to the most likely foundation systems encountered in the field.

Construction

Examine the construction issues involved in the proposed protected building.

Prepare an outline of construction specifications, including tolerances for component construction.

Examine the likelihood and the effect of the tolerances being exceeded.

Cost Estimate

Prepare a cost estimate based on construction costs in Canada / North America.

Prepare a cost estimate based on construction costs in Japan.

Examine the effect of the number of units constructed on the overall cost.

Reports

It is anticipated that for practical reasons three reports will be required:

Research Report - A comprehensive report of all phases of the research project.
Engineering Report - A specification of construction materials, processes and tolerances to be met in the construction of the Canadian Home with Isolation Protection. The engineering report should include a simplified design procedure for the proposed system, in a format similar to current building code procedures.
Marketing Report - A brief report intended to provide an effective summary of the research project for the purposes of gaining acceptance in the Japanese market.

11.2 Duration

It is estimated that the proposed work will be completed in about 18 months.

11.3 Budget

The estimated cost of the proposed activities is as follows:

Test preparation & planning	$10,000
Fabrication test specimens & materials	$50,000
Test execution	$30,000
Test data evaluation	$15,000
Analytical studies	$15,000
Practical detailed designs	$40,000
Final report & presentations	$15,000
TOTALS	**$175,000**

Each of the items above include cost estimates for materials, labour, supervision, project management, travel and administration costs.

■

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